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LIVINUS TUYISENGE

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Thèse dirigée par **LISSAN-EDDINE AFILAL**

JURY

M. Hacène FOUCHAL,	Professeur ,	Université de Reims Champagne-Ardenne,	**Président**
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M. Lissan-Eddine AFILAL,	Professeur,	Université de Reims Champagne-Ardenne,	**Directeur de thèse**
M. Samir TOHME,	Professeur,	UVSQ,	**Co-Encadrant**
M. Marwane AYAIDA,	Maître de Conférences,	Université de Reims Champagne-Ardenne,	**Co-Encadrant**

Table des matières

Introduction en Français

Contexte

Au cours de ces dernières années, la sécurité routière est devenue un des sujets les plus importants sur lesquels de nombreuses organisations ont porté leur attention. En Décembre 2018, les statistiques de l'Organisation Mondiale de la Santé (OMS) ont montré que chaque année, environ 1,35 million de personnes décèdent à cause des accidents de la route dans le monde [1, 2]. Par conséquent, ces accidents sont devenus la première cause de mortalité chez les jeunes (de 5 à 29 ans). Le signe alarmant était que 90% de ces accidents étaient dûs à des erreurs humaines du conducteur. Heureusement, depuis quelques décennies, l'évolution d'Internet continue de révolutionner de nombreux aspects de la vie quotidienne. Cela a commencé par la connexion des ordinateurs, puis les téléphones avant d'être généralisé à tout objet, ce qui a donné naissance au paradigme de l'Internet des Objets (IoT). Afin de résoudre ces problèmes de sécurité routière et grâce à ces progrès de la technologie des télécommunications, les véhicules peuvent maintenant avoir accès à Internet et sont dotés maintenant des capacités de communication. Tels sont les faits qui ont motivé l'introduction des Systèmes de Transport Intelligents (STI) et ainsi, l'introduction des réseaux véhiculaires ad hoc (VANETs). L'Internet des Véhicules (IoV) est donc une évolution de ces réseaux véhiculaires où l'IoT est appliqué et dans lequel le composant principal devient le véhicule.

Malgré ses nombreuses opportunités et avantages, de nombreux défis restent encore à relever dans l'IoV. L'un d'entre eux est le maintien d'une connectivité continue afin de fournir un environnement dit *"toujours connecté, à tout moment, n'importe où"* requis pour le déploiement de véhicules autonomes.

Problématique

Les réseaux véhiculaires sont des réseaux émergents qui connectent les véhicules les uns aux autres en utilisant des unités embarquées dans les véhicules (UeV) et l'infrastructure routière, aussi appelées : les Unités de Bord de route (UBR). Ils permettent de mettre en œuvre des applications de sécurité (prévention et évitement des collisions, annonces des zones des travaux, etc.), des applications temps réel (conduite autonome), des applications de systèmes de transport intelligents (gestion du trafic, suggestion de détour, etc.) et des applications de confort (péage automatique, consultation des médias en ligne, etc.). Le véhicule a donc besoin d'une communication quasi continue pour fonctionner correctement. Cependant, deux de leurs caractéristiques les plus importantes qui sont : leur grande mobilité et leurs fréquents changements de topologie dynamiques, sont assez critiques car ils génèrent des réseaux épars et discontinus. Pour cette raison, les réseaux véhiculaires ont besoin d'une densité de couverture élevée pour fonctionner efficacement. Malheureusement, le déploiement du standard de communications à courte portée (le DSRC) dédiées aux réseaux véhiculaires prendra du temps à cause de son coût onéreux en termes de déploiement des UBRs, estimé à 660 millions d'euros entre 2020 et 2026 [3, 4]. Il est donc intuitif d'utiliser d'autres réseaux déjà disponibles dans les véhicules, tels que les réseaux cellulaires des téléphones mobiles, en plus du réseau véhiculaire du standard IEEE 802.11p. Les réseaux cellulaires (3G, LTE, 4G) sont donc les meilleurs alternatifs grâce à leur large déploiement et leur accessibilité partout. Ceci est donc rendu possible grâce aux réseaux véhiculaires hétérogènes (HVN), qui consiste en l'hybridation de réseaux véhiculaires (IEEE 802.11p) et de réseaux cellulaires. Cependant, ces HVNs nécessitent la mise en oeuvre de mécanismes efficaces de gestion du transfert intercellulaire (communément appelé handover en anglais) permettant au véhicule de basculer rapidement, efficacement et à tout moment, entre les technologies de communication disponibles. Dans le reste du manuscrit, le terme de *transfert (inter)cellulaire* a été utilisé en français pour désigner le *"handover"*.

Motivations et objectifs

Le but et la motivation de cette thèse étaient donc de proposer des mécanismes permettant d'établir une connexion continue et qui puissent maximiser la communication entre les véhicules. Ainsi, nos principaux objectifs durant cette thèse sont:

- Réduire la latence du transfert intercellulaire, donc la réduction du délai de transfert.

- Diminuer et éventuellement éviter la perte de paquets, vu qu'elle peut être exprimée par la formule : perte de paquets = débit * durée de perte de paquets. De ce fait, la réduction du délai de transfert intercellulaire impliquera la réduction de la perte de paquets.

- Proposer ainsi un algorithme de transfert intercellulaire qui puisse sélectionner le meilleur candidat des réseaux disponibles à tout moment.
- Eviter l'effet ping-pong entre les transferts intercellulaires consécutifs.

Contributions

Au cours de cette thèse, nous avons proposé trois contributions afin d'atteindre notre objectif principal d'établir une connectivité continue dans le domaine de l'IoV.

Notre première contribution est la proposition et la conception d'un mécanisme de transfert vertical appelé PMIP-MIVH (Proxy MIPv6-based Mobile Internal Vertical Handover), qui utilise une interface logique et une architecture distribuée basée sur le standard PMIPv6, afin d'améliorer les performances du transfert intercellulaire et, par conséquent, les performances globales du réseau.

Notre seconde contribution est la proposition d'un algorithme basé sur la logique floue, permettant de sélectionner le meilleur réseau vers lequel s'effectue le transfert intercellulaire du véhicule, lorsque son réseau actuel devient faible alors que d'autres réseaux sont disponibles.

La troisième contribution est l'implémentation et la mise en œuvre de ces solutions proposées ci-dessus, dans le simulateur de réseau bien connu NS3 afin dévaluer ces solutions dans un scénario réaliste. Pour cela, nous avons intégré une librairie de la logique floue dans le simulateur NS3. Nous avons également étendu l'implémentation du protocole PMIPv6 dans NS3. En plus de cela, nous avons implémenté une fonctionnalité de type serveur de stockage facilitant la phase de collecte des données du transfert intercellulaire. Cette fonctionnalité permet de stocker dans des fichiers, les données charactérisant tous les réseaux disponibles et de les remonter pour une utilisation future lors de la phase de décision de l'algorithme de transfert intercellulaire.

Dans cette thèse, 3 publications furent faites :

1. Livinus Tuyisenge, Marwane Ayaida, Samir Tohme, Lissan-Eddine Afilal. *"Network Architectures in Internet of Vehicles (IoV): Review, Protocols Analysis, Challenges and Issues"*. Dans : International Conference on Internet of Vehicle (IoV). Springer. 2018, pp. 3–13
2. Livinus Tuyisenge, Marwane Ayaida, Samir Tohme, Lissan-Eddine Afilal. *"Handover Mechanisms in Internet of vehicles (IoV): survey,*

Trends, Challenges, and Issues". Dans : Global Advancements in Connected and Intelligent Mobility: Emerging Research and opportunities, 2019 IGI Global.pp. 1–64

3. Livinus Tuyisenge, Marwane Ayaida, Samir Tohme, Lissan-Eddine Afilal. *"A Soft Logical Interface PMIPv6-based Handover Mechanism in VANETs"*. Dans : Global Communications Conference (GLOBECOM), 2019 IEEE. pp. 47–55
Une quatrième publication est en cours de révisions mineures au moment de la rédaction de ce manuscript:

4. Livinus Tuyisenge, Marwane Ayaida, Samir Tohme, Lissan-Eddine Afilal. *"A Mobile Internal Vertical Handover Mechanism for Distributed Mobility Management in VANETs"*. Soumis pour publication dans : Journal of Vehicular Communications, 2019 Elsevier

Plan de la thèse

Cette thèse est organisée comme suit :

Tout d'abord, dans le chapitre 2, nous commencerons par un aperçu sur les différents types de communications entre les véhicules dans la section 2.1, ensuite, nous présenterons les architectures présentes dans l'IoV dans la section 2.2 et nous verrons les opérations de base du transfert cellulaire dans la section 2.3. Nous décrirons les phases du transfert vertical intercellulaire dans la section 2.4, avant de proposer notre classification des types de transfert dans la section 2.5, suivie de leur description.

Un focus sur les points forts des approches de transfert géré par le réseau ainsi que ceux des approches de gestion distribuée de la mobilité seront abordés respectivement dans les sections 2.5.3.2 et 2.5.5.2, du fait que les solutions que nous proposons dans cette thèse seront basées sur ces approches.

Ensuite, dans le chapitre 3, après avoir constaté les avantages des réseaux cellulaires, notamment leur couverture et leur disponibilité partout dans le monde, de plus, vu les contraintes de connectivité continue imposées par les réseaux véhiculaires, nous avons jugé pertinent d'étudier et d'intégrer la technologie LTE dans nos travaux. C'est ainsi que nous avons consacré ce chapitre à l'étude des protocoles et des algorithmes utilisés dans le transfert intercellulaire dans les réseaux hétérogènes incluant le LTE. Ainsi, nous commencerons dans la section 3.1, par une vue globale des protocoles de transfert intercellulaire dans les réseaux LTE. Nous y aborderons également, dans la sous-section 3.1.1, les standards MIH et ANDSF, facilitant un transfert transparent; suivi de l'étude de la prise en charge du protocole PMIPv6 dans LTE, présentée dans la section 3.1.2. Ensuite, les améliorations de LTE, requises pour supporter les services V2X, seront données dans la section 3.2. Afin de mieux comprendre les méthodes que nous avons utilisées dans les solutions que nous proposons, nous avons consacré une section 3.3, dans laquelle nous verrons le concept des méthodes de prise de décision multi-critères (MADM) dans la section 3.3.1, la méthode AHP (Analytic Hierarchy Process) dans la section 3.3.2, et enfin, la théorie de la logique floue dans la section 3.3.3.

Ensuite, dans le chapitre 4, nous décrirons notre approche de transfert vertical intercellulaire : le PMIP-MIVH que nous avons proposé, dans la section 4.1. Après cela, nous présenterons un cas d'utilisation de notre approche dans la section 4.2, avant de proposer un modèle analytique de notre approche dans la section 4.3 et la discussion des résultats analytiques dans la section 4.4.

Dans le chapitre 5, nous proposerons des algorithmes de sélection du meilleur réseau candidat. Nous allons donc commencer par une proposition d'une méthode basée sur AHP dans la section 5.1. Ensuite, dans la section 5.2, nous définirons notre métrique de qualité de service attendue en proposant une fonction de compromis entre les exigences de l'application et le service offert par chaque réseau disponible, avant de l'utiliser dans un sytème d'inférence des règles en utilisant le logique floue dans la section 5.3.

Ensuite, dans le chapitre 6, nous verrons en détail dans la section 6.1, les étapes de la mise en oeuvre et implémentation de ces solutions dans NS3. Les résultats des simulations de PMIP-MIVH seront discutés dans la section 6.2 tandis que les résultats des simulations intégrant l'algorithme basé sur la logique floue que nous avons proposé, seront donnés et discutés dans la section 6.3. Enfin, nous conclurons dans le chapitre 7.

Synthèse de la thèse

État de l'art et notions de base

Description des réseaux véhiculaires

Les réseaux véhiculaires (VANETs pour *Vehicular Ad-hoc Networks*) sont des réseaux émergents, consistant en un cas particulier de réseaux mobiles ad hoc (MANETs pour *Mobile Ad-hoc Networks*) dans lesquels le nœud principal devient le véhicule.

Cependant, l'écosystème des VANETs, et par conséquent de l'Internet des Véhicules (IoV), est constitué d'autres composants formant le Système de Transport Intelligent Coopératif (STI-C). Parmi ceux-ci, il y a l'infrastructure routière composée d'unités de bord de route (UBR) reliées au réseau central de gestion du trafic via une station ITS centrale (ITS-C). En Europe, toutes les stations ITS sont basées sur la pile ITS normalisée par l'Institut Européen de Normalisation des Télécommunications (ETSI). Les UBRs (appelés ITS-R) et les véhicules (appelés ITS-V) communiquent via des réseaux sans fil (couche d'accès) basés sur le réseau ITS-G5 (héritant de la norme IEEE 802.11p). Les principaux types de communication dans les réseaux véhiculaires sont ainsi les suivants:

- Véhicule à véhicule (V2V),
- Véhicule à l'infrastructure (V2I)
- Véhicule à piétons (V2P)
- Véhicule aux Capteurs (V2S)
- Véhicule à tout (V2X), et récemment,
- Cellulaire-Véhicule à tout (C-V2X)

Les architectures de l'IoV

Le niveau élevé de mobilité et le changement dynamique de la topologie, qui caractérisent les réseaux véhiculaires, rendent difficile le déploiement et les applications des véhicules connectés. Cependant, le développement important et très rapide des systèmes de télécommunications et, plus récemment, le déploiement de l'Internet des Objets (IoT) ont permis de contribuer significativement dans ce domaine. Ainsi, plusieurs architectures de communication pour l'IoV ont été proposées et sont principalement basées sur plusieurs couches. C'est pourquoi, dans cette thèse, nous avons revisité ces architectures et avons accordé une grande importance au transfert intercellulaire basé sur plusieurs couches, comme cela sera détaillé dans la section 2.5.

Notions de base sur le tranfert intercellulaire

Le terme *"tranfert intercellulaire"* (handover ou handoff en anglais) fait référence au fait de transférer un appel ou une session de données en cours, d'un *Point d'Attachement (PoA)* à un autre *sans interruption de service*. Lorsqu'un transfert se produit entre des cellules d'une même technologie d'accès radio, le processus est appelé transfert horizontal. En revanche, le transfert vertical est un terme qui désigne le transfert entre des vecteurs de technologie d'accès réseaux hétérogènes tel est notre cas de réseaux véhiculaires hétérogènes (HVN).

Cependant, le problème le plus important est de savoir *"quand"* et *"vers où"* effectuer ce transfert. Pour cela, trois phases principales interviennent dans ce processus :

1. La phase de collecte des informations de transfert
2. La phase de décision du transfert
3. La phase d'exécution du transfert

Nous avons ainsi proposé dans la section 2.5 une classification des principales approches de transfert intercellulaire existantes dans la littérature, nous les avons ensuite décrites et avons donné quelques solutions qui les utilisent, ainsi que leurs extensions.

Étude des algorithmes et protocoles de handover dans les réseaux hétérogènes avec LTE

Après avoir fait cette classification des méthodes existantes et vu les contraintes de connectivité continue imposées par les réseaux véhiculaires, nous avons jugé pertinent d'étudier et d'intégrer la technologie LTE dans nos travaux, grâce à ses avantages notamment sa couverture et sa disponibilité partout dans le monde. Nous avons alors commencé par étudier comment ces solutions de transfert sont actuellement utilisées dans la technologie LTE.

Ainsi, dans le chapitre 3, nous avons commencé par étudier les principaux composants du système LTE afin d'en déduire leurs principaux rôles dans le processus de tranfert cellulaire, avant de les utiliser dans l'étude des protocoles de transfert intercellulaire (tels que MIH, ANDSF, PMIPv6) et des algorithmes de transfert appliqués et utilisés dans la technologie LTE. Des améliorations de LTE, requises pour prendre en charge les services V2X, ont étées aussi étudiées dans ce chapitre. C'est ainsi qu'ensuite, nous avons étudié les méthodes que nous pourrons utiliser pour faire une décision basée sur plusieurs critères dont celles recommendées par ces améliorations.

Méthodes de décision multi-critères : Cas de l'AHP et de la Logique Floue

Compte tenu de la complexité des systèmes actuels et de leurs opérations lourdes, il est devenu plus difficile de disposer de méthodes plus précises pour choisir entre deux ou plusieurs systèmes complexes. C'est le cas du transfert vertical dans les réseaux véhiculaires hétérogènes, dans lequel un meilleur réseau doit être choisi en temps réel afin d'assurer la meilleure continuité de service lorsque des véhicules passent d'un réseau à un autre. Pour cela, toute décision doit être prise en tenant compte de nombreux paramètres. Divers algorithmes de prise de décision multi-critères (MADM) qui traitent cette complexité de décision ont été proposés dans la littérature. Nous avons choisi d'utiliser deux méthodes : la procédure d'Analyse Hiérarchique (AHP) gràce à son principe de diviser pour mieux régner, et la logique floue grâce à sa capacité de traitement des informations imprécises, qui est plus proche du raisonnement humain.

La Procédure d'Analyse Hiérarchique (AHP)

La méthode AHP est une méthode d'aide à la décision se basant sur la hiérarchisation des critères. Selon son pionnier et fondateur, Thomas L. Saaty, à la fin des années 1970 [5, 6], la méthode AHP est une technique structurée pour organiser et analyser des décisions complexes, basée sur les mathématiques et la psychologie. Pour ces raisons, elle est largement utilisée dans de nombreuses situations de décision à travers le monde [7], plus particulièrement dans les domaines tels que la gouvernance, le commerce [8, 9], l'industrie [10, 11], la santé, le transport [12], l'éducation, etc.

Elle est basée sur le principe de diviser pour mieux régner. Le problème principal est divisé en sous-problèmes, chaque sous-problème étant évalué en tant que facteur de décision. De l'ensemble des solutions alternatives, AHP finit par trouver la solution la plus optimale. Afin de décomplexifier la situation de décision, l'AHP divise le processus de décision en étapes hiérarchiques, en tenant compte de l'importance (poids) de chaque élément décisionnel par rapport à un autre, avant d'arriver à la solution finale. Cela prouve à quel point l'AHP peut être plus bénéfique dans des situations très complexes, telles que sont les situations de décision de véhicules autonomes.

La Logique Floue et les commandes floues

La plupart des paramètres utilisés dans la phase de décision des algorithmes de transfert vertical en IoV proviennent des capteurs. Par conséquent, en raison de la vitesse des véhicules, les informations collectées peuvent souvent être imprécises, des fois avec un degré d'incertitude élevé. De plus, le fait que de nombreux paramètres doivent être utilisés dans le transfert vertical, les algorithmes de calcul sont très importants et sont fréquemment utilisés lors de la phase de décision.

Pour traiter cette question d'incertitude des informations recueillies, la théorie de la logique floue et les techniques de réseaux de neurones sont souvent appliquées. Habituellement, ces algorithmes sont appliqués en premier afin de convertir des données imprécises en données précises. Ensuite, un algorithme MADM est alimenté avec ces données pour déterminer le meilleur choix [13, 14, 15, 16].

La Logique Floue est ainsi basée sur un ensemble de commandes appelées commandes floues (Fuzzy Logics controllers : FLCs). Chaque commande floue fonctionne selon les étapes suivantes :

- La fuzzification : c'est une étape permettant de déterminer le degré d'appartenance d'une donnée d'entrée à chacun des variables floues (variables linguistiques correspondant à des sous-ensembles flous) appropriés (par exemple : faible, moyen, élevé) via des fonctions d'appartenance (exemple : triangulaire, gaussienne, trapezoïdale) [17].

- Un moteur d'inférence : ce processus traite les entrées fuzzifiées et les corrèle aux sorties en utilisant des règles “ SI condition ALORS action ”, qui sont prédéfinies dans la base de règles en tant que base de connaissances. Notez que chaque règle donne en sortie une mesure exprimée en degré d'appartenance, calculée à l'aide d'une fonction d'appartenance prédéfinie (par exemple gaussienne, triangulaire, etc.).

- L'agrégation : après l'inférence, les degrés de sortie de toutes les règles de la phase d'inférence doivent être agrégés (à l'aide d'un opérateur d'agrégation prédéfini). Cela donne une sortie fuzzifiée.

- La défuzzification : la sortie fuzzifiée de l'agrégation est défuzzifiée en utilisant l'une des méthodes de défuzzification disponibles (MinOfMax, Centroid, centre de gravité, etc.) afin d'obtenir une valeur discrète finale de sortie à utiliser dans le processus de prise de décision.

Concrètement, les paramètres en entrée sont introduits dans un fuzzifier qui les convertit un à un en sous-ensembles flous en déterminant à quel degré la valeur du paramètre en entreé appartient à chacun des sous-ensembles flous relatifs à ce paramètre, via des fonctions d'appartenance. Ensuite, ces ensembles flous sont envoyés à un moteur d'inférence de la logique floue en vue d'une application des règles "SI...ALORS ..." contenues dans une base de connaissances, ce qui produit en sortie d'autres sous-ensembles flous relatifs aux paramètres en sortie. Ces derniers sont ensuite accumulés/aggrégés dans un seul ensemble flou et livré au defuzzifier pour une reconversion finale en une valeur discrète précise, qui peut enfin être utilisée dans prise de décision finale du transfert [18].

PMIP-based Mobile Internal Vertical Handover

Après l'étude et l'analyse approfondies des solutions de transfert intercellulaire existantes, nous avons constaté que malgré leurs avantages et leurs différentes manières de gérer les étapes du processus de transfert, le problème fondamental et commun était toujours de trouver le moment le plus approprié pour déclencher le transfert et minimiser les coûts en termes de paquets échangés et d'impact du transfert. En effet, le niveau élevé de mobilité des VANETs et leur évolution dynamique de la topologie rendent très difficile la prédiction de la durée pendant laquelle le véhicule restera connecté à un réseau. En effet, cette prévision devrait être basée sur de nombreux paramètres (tels que la vitesse, la direction, le signal du réseau, la distance entre les véhicules et les RSUs, etc).

Malgré cette difficulté de prédiction, la plupart des solutions existantes reposaient souvent sur le niveau du signal reçu (RSSI) avant de décider de déclencher le transfert. Cela conduisait toujours à un temps critique de déconnexion, souvent appelé la durée de latence du transfert. Cela a un impact négatif sur les performances des applications, telles que la perte de paquets. Ce dernier risque de nuire à certains types d'applications, telles que les applications de sécurité et les applications temps réel. Nous avons pris en compte cette difficulté d'avoir une bonne méthode de prédiction, et nous avons analysé les conséquences néfastes du temps de déconnexion qui en découle lors des transferts intercellulaires, et plus particulièrement dans des applications critiques telles que la conduite autonome. Nous nous sommes donc focalisés à la recherche d'un moyen de réduction de ce temps de déconnexion et ainsi de ses impacts négatifs.

C'est pourquoi, afin de répondre à ce problème de *"Quand?" déclencher le tranfert*, nous avons proposé notre mécanisme de transfert vertical appelé (PMIP-MIVH) [19] que nous présentons dans le chapitre 4. Notre approche PMIP-MIVH consiste en *une anticipation du potentiel prochain transfert intercellulaire* en permettant au véhicule de se connecter directement et simultanement à tout nouveau type de réseau disponible, tout en restant connecté au réseau courant. Pour cela, notre mécanisme de transfert vertical utilise une interface logique et une architecture distribuée basée sur le standard PMIPv6 afin d'améliorer les performances du transfert intercellulaire.

Fonctionnement de l'approche

Pratiquement, notre interface logique joue le rôle de transmission et de réception de données, tandis que les multiples interfaces physiques jouent le rôle de signalisation, d'accès radio et de plan de contrôle. Ainsi, lorsque le mobile a besoin de recevoir des données, il vérifie d'abord la disponibilité de la connectivité en appelant une méthode *interface::IsUp* que nous proposons sur l'interface logique, et qui déclenche par conséquent une méthode *IsUp()* sur chacune des interfaces physiques installées dans le véhicule. À l'aide de la conjonction OU, l'interface logique vérifie qu'au moins une interface est active et connectée sur ce mobile. Cela consiste en la vérification pour voir si au moins une des interfaces est capable de recevoir les paquets.

Si au moins une interface est connectée, le mobile peut donc recevoir les données sans se demander si l'interface physique correspondante est hors service ou non. Ceci est possible grâce à la mise en place d'un tunnel de réception entre l'interface logique et chaque interface active.

En général, faute d'avoir une méthode efficace de prédiction du bon moment de transfert, c'est souvent à ce moment-là où l'interface physique correspondante serait hors service ou déconnecté, que le mobile devrait tout d'abord déclencher le processus de transfert afin de pouvoir recevoir ces données. Il en est évident que si aucun système tampon pour ces paquets n'a pas été mis en place, ces paquets seraient perdus. **C'est à ce niveau-là qu'avec notre approche, nous arrivons à gagner et à améliorer le temps de latence du handover, le taux de réception et le débit du système, par rapport aux autres solutions existantes**. Ainsi, avec notre approche, la communication avec le correspondant distant peut continuer même s'il est possible que des changements se soient produits dans les états de l'interface physique (voir MIH dans la section 3.1.1). Par cette méthode, nous arrivons ainsi à assurer la continuité de la session vis-à-vis du correspondant, grâce aux fonctionnalités de l'interface logique.

Ainsi, notre algorithme commence au démarrage du mobile, quand le véhicule n'est connecté à aucune interface réseau. Ensuite, lorsqu'il arrive dans la couverture du premier réseau disponible, il s'y connecte simplement de la manière habituelle. À ce stade, il se connecte au réseau et applique le principe du "Best Effort". Ensuite, le mobile doit surveiller d'autres réseaux potentiels auxquels il peut se connecter. Dès qu'un autre réseau devient disponible, le mobile doit anticiper le processus d'un potentiel prochain transfert intercellulaire. Raison pour laquelle, le mobile se connecte directement à ce réseau en utilisant l'architecture distribuée de PMIPv6. C'est après cette connexion que l'interface logique intervient pour la réception et la transmission des données. Par ailleurs, le mobile continue à surveiller de potentielles déconnexions et la disponibilité de nouveaux réseaux.

Nous avons ainsi donné un exemple de cas d'utilisation : le monitoring à distance d'une conduite autonome, dans lequel nous avons appliqué notre mécanisme de transfert vertical. Nous avons également proposé le modèle analytique et avons discuté de ses résultats numériques. L'analyse numérique de ce modèle montre que notre solution proposée (PMIP-MIVH) fonctionne bien en termes de nombre de paquets reçus, de latence de transfert et de la continuité de session. Ceci prouve aussi que notre solution a bien amélioré le processus de transfert intercellulaire. Les résulats des simulations utilisant notre approche sont détaillées dans la section 6.2.

Proposition de méthodes et algorithmes de sélection du meilleur réseau dans les VANETs

Dans le chapitre 5, nous avons abordé le problème de *"Vers où ?"* effectuer le transfert vertical en utilisant la méthode MADM AHP et la théorie de la logique floue que nous avions déjà décrites dans la section 3.3.

Méthode de sélection de candidat basée sur l'AHP

Dans le but de proposer une méthode de sélection du meilleur candidat, nous avons tout d'abord proposé d'utiliser la méthode AHP grâce à ses avantages décrits dans la section 3.3.2. Pour cela, nous avons tout d'abord proposé l'utilisation de l'hiérarchie composée par 3 principaux niveaux : l'objectif (Choisir le meilleur réseau disponible), les critères (niveau du signal, bande passante, latence du réseau, vitesse du véhicule, gigue, QoS), et les alternatives (WiFi, IEEE 802.11P, 3G, LTE, WiMAX). Nous avons ainsi appliqué les étapes de la méthode AHP en passant par les différentes comparaisons des critères deux à deux, puis des alternatives deux à deux, selon l'importance de chacun d'eux dans la réalisation de notre objectif. Nous avons finalement réussi à classer les alternatives en fonction de leurs scores finaux dans la réalisation de l'objectif principal : meilleur réseau selon les critères de transfert considérés.

Cependant, nous avons constaté que ces résultats sont tellement dépendants du scénario testé et sont difficiles à généraliser, surtout en cas d'applications temps réel où les valeurs des critères changent fréquemment, comme c'est le cas du handover vertical dans les VANETs. De ce fait, nous avons constaté que les résultats AHP sont très dépendants du poids attribué à chaque critère ou alternative lors des comparaisons par paires. En raison de cette dépendance spécifique à l'utilisateur/concepteur, AHP exige au préalable une bonne expérience et une expertise dans le domaine. Ainsi, nous reprochons à cette méthode sa **faiblesse en termes de flexibilité et d'injection des données après la conception du système**. En outre, dans de nombreux cas, plusieurs experts (ou décideurs) doivent être consultés au préalable. De cette expérience, nous avons pu juger que le processus de comparaison des décisions utilisant l'AHP est plus approprié pour les décisions statiques qui ne doivent pas changer fréquemment et rapidement. De plus, les termes de comparaison utilisés dans le processus de comparaison AHP peuvent être ambigus ou peuvent avoir des valeurs différentes d'un expert/décideur à l'autre. Cela pourrait ne pas aboutir à un consensus dans le processus de décision. Pour pallier à ce problème, nous avons suggéré d'utiliser plutôt la théorie de la logique floue dans le traitement de ce genre de données utilisées dans la décision du handover vertical dans les VANETs.

Proposition d'une fonction de compromis pour la Qualité de Service Espérée

Partant des différents points de vue sur les notions de la qualité de service (QoS) et de qualité d'expérience (QoE) (points de vue IETF et IUT-T [20, 21, 13]), nous avons vu que les préférences de l'utilisateur, les exigences de l'application et les capacités du réseau doivent être prises en compte afin de concevoir une stratégie et une technique efficaces de transfert vertical. Par conséquent, nous avons ainsi proposé et conçu une fonction de compromis que nous avons appelée Fonction de Compromis de qualité de service espérée (Expected QoS Tradeoff Function).

Cette fonction prend en compte certains des paramètres techniques de la qualité de service (bande passante, perte de paquets, latence, gigue), recommandés dans l'améliorations du LTE pour le support des services V2X, et dont la dégradation peut impliquer directement la dégradation de la qualité d'expérience de l'utilisateur. Nous avons ainsi considéré ces paramètres comme le minimun des exigences en QoS dont une application a toujours besoin pour fonctionner correctement.

Ainsi, cette fonction procède à des comparaisons par paires en calculant pour chaque paramètre, le rapport entre les exigences de l'application et les performances offertes par chaque réseau disponible. La sortie de cette fonction donne alors la valeur de notre métrique "Expected QoS" résultant de l'aggrégation de ces rapports multipliés par le poids de chaque paramètre dans la décision finale. Notons que, pour ne pas diviser par zéro, un paramètre dont l'offre réseau est égale à zéro n'est pas pris en compte pour ce réseau. Il est ignoré en lui attribuant un poids égal à zéro.

Par la suite, c'est cette nouvelle métrique que nous utiliserons avec les autres paramètres (niveau du signal et la vitesse), en utilisant la méthode de la logique floue, afin de sélectionner le meilleur réseau candidat vers qui effectuer un transfert vertical.

Algorithme basé sur la Logique Floue

En s'inspirant du principe de "diviser pour mieux reigner" de la méthode AHP, nous avons choisi de concevoir un algorithme spécifique au type d'applications qui nous intéresse. L'ensemble du problème (objectif) de recherche du meilleur réseau est divisé en de sous-problèmes ou sous-module (réalisation pour chaque réseau, des comparaison par paire de chaque exigence de l'application avec le paramètre réseau respectif vis-à-vis du bon fonctionnement de cette application). Chaque sous-module correspond donc à chaque réseau disponible, faisant office d'un élément influant sur la décision globale.

Il s'agit d'un algorithme de transfert intercellulaire vertical dans les réseaux véhiculaires hétérogènes (HVNs), basé sur le compromis " exigences de l'application - Capacités réseau ", et utilisant la logique floue. Afin d'utiliser plus de paramètres en vue d'un transfert vertical efficace et précis, nous avons conçu cette approche transversale (multi-niveaux ou crosslayer en anglais) en prenant en compte les exigences de l'application, grâce à notre métrique de qualité de service, exprimée en termes de rapport entre l'offre de chaque réseau disponible par rapport aux exigences de l'application.

Nous avons ainsi conçu un système d'inférence floue pour chaque réseau, qui utilise 3 paramètres en entrée, à savoir : le niveau du signal reçu (RSSI), la vitesse du véhicule et la qualité de service attendue (Expected QoS) pour les réseaux ITS G5 et WiFi. Pour le LTE, nous avons utilisé le signal (RSRQ) donnant plus d'informations sur la qualité du signal reçu dans un bloc de ressources, à la place du niveau du signal reçu (RSSI) qui inclut aussi le signal bruit et les interférences mesurées sur toute la bande passante. L'implémentation et les résulats de cette méthode sont reportés dans la section 6.3.

Implémentation et résultats des simulations

Dans le chapitre 6, nous avons présenté l'implémentation et les résultats des simulations de ces solutions proposées. Nous avons commencé dans la section 6.1 par détailler l'implémentation et les modifications apportées dans NS3 pour pouvoir mettre en oeuvre ces solutions. Nous avons surtout détaillé l'intégration de la méthode de la logique floue dans NS3. Puis, dans la section 6.2, nous avons discuté des résulats de simulation de notre méchanisme de transfert vertical PMIP-MIVH. Ensuite, nous avons présenté et discuté les résultats de simulation intégrant l'algorithme basé sur la logique floue dans la section 6.3. Tous ces résultats montrent que nos solutions permettent d'améliorer les méchanismes de transfert intercellulaire dans les réseaux véhiculaires.

Conclusion générale et perspectives de la thèse

Conclusion générale

Le déploiement des véhicules connectés et autonomes permet de nouveaux modes de transport et de nombreux nouveaux marchés ont été déjà créés dans ce domaine. Cependant, les véhicules autonomes sont très challengeants et nécessitent une coordination efficace entre les nombreuses tâches et opérations qui permettront aux véhicules de prendre leurs propres décisions, sans une intervention humaine.

Dans le chapitre 2, nous avons proposé un état de l'art et présenté des notions de base sur les avancées et progrès déjà réalisés dans ce domaine de l'internet des voitures (IoV). Nous avons souligné les problèmes de communication et de connectivité continue des véhicules. Nous avons ainsi passé en revue les mécanismes à mettre en œuvre afin d'assurer un transfert intercellulaire transparent entre les réseaux disponibles, permettant ainsi aux véhicules de passer d'un réseau à un autre tout en maintenant la continuité de la session (c'est-à-dire sans perdre la connectivité et les capacités de communication).

Tout d'abord, une analyse des architectures de déploiement de l'IoV et des communications D2D récemment proposées dans la littérature a été présentée dans ce chapitre. L'objectif principal et la contribution de cette partie étaient de montrer pourquoi et comment les mécanismes de transfert multi-niveaux (multicouches) sont essentiels dans le domaine de l'IoV et au déploiement de voitures autonomes. Dans la section 2.5, nous avons proposé notre propre classification des mécanismes de transfert existants dans les réseaux cellulaires et véhiculaires. Nous avons défini les critères de classification tels que les vecteurs et la fréquence de communication, le mode d'exécution du transfert intercellulaire, l'acteur décisionnel du transfert intercellulaire, le nombre de couches (niveaux) impliquées pendant le transfert, le type d'architecture utilisée pour exécuter le transfert et l'événement qui déclenche l'initiation du transfert. Ainsi, sur la base de ces critères, nous avons proposé une classification récente en incluant et en soulignant les avantages des approches de gestion distribuée de la mobilité qui sont récentes dans la littérature et dont certaines activités de standardisation sont toujours en cours.

Dans le chapitre 3, nous avons fait une étude sur les protocoles de gestion de transfert intercellulaire dans les technologies LTE. Les améliorations du standard LTE pour la prise en charge des services V2X ont été étudiées dans la section 3.2. Dans la section 3.3, nous avons montré à quel point la phase de décision est très complexe et qu'elle doit être bien conçue pour permettre un transfert vertical fiable et efficace. Nous avons ainsi donné une vue globale sur certaines des méthodes de prise de décision multi-critères les plus populaires dans ce domaine, tout en mettant en évidence les avantages de la méthode AHP et ceux de la logique floue.

Ensuite, dans le chapitre 4, nous avons proposé notre mécanisme de transfert vertical appelé "Proxy MIPv6-based Mobile Internal Vertical Handover (PMIP-MIVH)", qui utilise une interface logique et un schéma PMIPv6 distribué afin d'améliorer les performances du transfert intercellulaire et, par conséquent, les performances globales du réseau. Nous avons proposé un modèle analytique et des analyses numériques ont été décrites dans ce chapitre.

Dans le chapitre 5, nous avons proposé notre algorithme de sélection du meilleur réseau candidat pour le transfert vertical, qui est basée sur la logique floue, et qui a permis d'améliorer les performances de notre approche proposée PMIP-MIVH. Dans cet algorithme, nous avons défini notre critère de qualité de service, que nous avons appelée qualité de service attendue (espérée), qui repose sur un rapport de compromis entre les exigences de l'application et les capacités de performance offertes par le réseau.

Ensuite, dans le chapitre 6, nous avons présenté l'implémentation et les simulations des deux solutions proposées en utilisant le simulateur de réseau bien connu et l'un des plus utilisés NS3. Nous avons décrit et effectué les mesures de performance en termes de taux de réception de paquets (PDR), de taux d'erreur de paquet (PER), de délai, de gigue et de débit.

Les résultats des simulations ont confirmé les résultats analytiques. En effet, ces résultats ont montré que notre approche PMIP-MIVH proposée surpasse les solutions existantes, en termes de performances. De plus, l'utilisation de la logique floue a contribué fortement à l'amélioration des performances de notre mécanisme de transfert vertical (PMIP-MIVH) proposé.

Perspectives

Les mécanismes de transfert verticaux efficaces et les améliorations LTE pour le support des services V2X nécessitent encore de nombreux efforts dans les domaines de la recherche industrielle et académique, et une bonne collaboration entre ces deux mondes est considérée avec la plus grande attention pour les déploiements des transports intelligents et autonomes. Nous souhaitons continuer à contribuer à approfondir ce domaine afin de proposer et de trouver des solutions efficaces nécessaires à un meilleur déploiement des véhicules connectés et autonomes, à la mobilité intelligente et au déploiement du transport intelligent. Dans un avenir proche, nous voulons continuer à concevoir un algorithme de décision de transfert intercellulaire plus efficace afin d'améliorer les performances des solutions proposées. Ainsi, nos perspectives à court termes se concentreront donc sur :

- L'étude de l'impact des paramètres de pondération sur la métrique Expected QoS
- Le test des différentes méthodes de la Logique Floue (fonction d'appartenance, inférence, defuzzification)
- L'évaluation de l'intérêt de l'utilisation de Takagi-sugeno par rapport à Mamdani (à savoir par exemple la réduction du nombre de règles)
- L'implémentation sur boitier et la réalisation des tests sur table des solutions proposées

Ensuite, nos perspectives à long termes porteront sur :

- La préparation et la réalisation des expérimentations sur piste
- L'implémentation de la gestion des flux pour un meilleur usage des ressources quand le véhicule reste longtemps connecté simultanément sur plusieurs réseaux.

De plus, afin d'avoir des mécanismes de transfert intercellulaire transparents et efficaces pour le déploiement des véhicules autonomes, beaucoup de problèmes et de défis suivants restent encore à relever:

- QoS : vu que les véhicules auront toujours des applications temps réel et non temps réel de façon simultanées, un plus grand nombre de paramètres doit être pris en compte afin de toujours garantir une excellente qualité de service à ces différentes types d'applications.
- Performances TCP : dans les communications à base du protocole TCP, de nombreux mécanismes de contrôle du flux de congestion sont utilisés et sont souvent basés sur la bande passante et la fenêtre de congestion. De ce fait, dans ces réseaux véhiculaires hétérogènes, lorsque le transfert intervient entre un réseau à faible bande passante et à haut débit vers un réseau de bande passante élevée et réseau à faible débit de

données, les performances TCP peuvent se dégrader fortement. Des mécanismes spéciaux pour les HVNs doivent être développés pour résoudre ce problème.

- Sécurité : étant donné que les communications véhiculaires utilisent le mode "hors du contexte de base du point d'accès" (Outside of the Context of Basic service set en anglais), certains mécanismes d'authentification et d'autorisation ne sont pas pris en compte lors de la communication, ce qui peut être une source de faille de sécurité et de piratage. Ce domaine doit continuer à être bien étudié afin de garantir la fiabilité des communications véhiculaires, et particulièrement dans les cas de transfert intercellulaire, tout en maintenant simultanément une faible latence et de faible gigue.

- Planification et routage intelligents : étant donné la grande mobilité et les fréquents changements de topologie dans les VANETs, un transfert intercellulaire efficace doit impérativement prendre en compte la prédiction de la position et de la direction comme critère principal lors de la prise de décision. C'est pour cette raison que la planification de la trajectoire est un défi qui doit être résolu lors de la prise de décision relative aux véhicules autonomes en milieu urbain. Ainsi, elle permet aux voitures autonomes de trouver les itinéraires les plus sûrs, les plus pratiques et les plus économiquement avantageux d'un point de départ à une destination.

- Les capteurs & intelligence artificielle : le véhicule interagit en permanence avec son environnement grâce à un certain nombre de données de capteurs. Ces données détectées par différents capteurs doivent être fusionnées avant d'être utilisées pour prendre une décision. Actuellement, l'intelligence artificielle est une technologie clé utilisée dans ce domaine et doit être bien testée dans différents scénarios réels avant que les passagers d'un véhicule autonome ne puissent l'utiliser en toute confiance.

- Traitement massif de données en temps réel : une bonne combinaison de traitement parallèle et séquentiel de données est nécessaire dans les scénarios où seul le traitement parallèle de données ne suffit pas. Une acquisition et un traitement parallèles des données sont nécessaires lors de la prise de décision multi-critères d'un transfert intercellulaire.

- Précision dans la géolocalisation : lors du routage des paquets et la planification de l'itinéraire, il est essentiel de disposer d'un système de géolocalisation et de navigation précis. Ce système de navigation doit également permettre une synchronisation efficace entre tous les composants du réseau véhiculaire (véhicules, UBR, capteurs, lidars, caméras, etc.). Le système de navigation pourrait être amélioré à l'aide des approches de partage de capteurs et de perception de l'environnement afin de bien contrôler le comportement du véhicule, et par conséquent, prédire la position future du véhicule concerné.

- Services réseau et capacités informatiques de pointe : les exigences telles que la latence, la fiabilité, le débit et l'évolutivité doivent être remplies. Cela implique et suppose également la disponibilité de dispositifs informatiques avancés et de la mémoire dans les véhicules ou des capacités de Cloud Computing et de données volumineuses. Voici quelques exemples de services de réseau pouvant être fournis:
  - Services Cloud, connexion à Internet
  - Multi-access Edge Computing (MEC) pour les applications critiques et ne tolérant pas le temps de latence
  - Assistance réseau pour un positionnement extrêmement précis

À long terme, nous voulons continuer à étudier et à proposer des solutions à ces divers défis.

Abstract

Vertical handover is one of the key technologies that will facilitate the connected and autonomous vehicles deployment. Today, the emergence of Vehicular Ad-hoc NETworks (VANETs): Vehicle-to-Vehicle (V2V) communications, Vehicle-to-Infrastructure (V2I) and Vehicle-to-Everything (V2X) has enabled new applications such as Cooperative Intelligent Transport Systems (C-ITS), real-time applications (for example, autonomous driving), road traffic management applications and comfort applications. However, these networks are characterized by a high level of mobility and dynamic change in the topology, which generates scattered networks and requires handover mechanisms for maintaining ongoing session continuity. To address this problem, we have proposed a PMIP-based Mobile Internal Vertical Handover (PMIP-MIVH) approach which takes advantage of the use of a logical interface in handling handover. To improve and extend our approach, a cross-layer and fuzzy logic-based selection method of the best available network has been also proposed. Analytical results and conducted simulation results, all show that the proposed solutions overperform the existing handover mechanisms and enhance efficiently the handover management in the vehicular networks.

Résumé

Le transfert vertical intercellulaire (Handover) est l'une des technologies clé qui facilitera le déploiement des véhicules connectés et autonomes. Aujourd'hui, l'émergence des réseaux véhiculaires : les communications de Véhicule à Véhicule (V2V), Véhicule à Infrastructure (V2I) et de Véhicule à tout (V2X), a permis de nouvelles applications telles que les Systèmes de Transport Intelligents Coopératifs (C-ITS), les applications temps réel (par exemple, la conduite autonome), applications de gestion du trafic routier et applications de confort. Cependant, ces réseaux se caractérisent par une grande mobilité et de fréquents changements de la topologie, ce qui génère des réseaux épars et nécessitant des mécanismes de transfert pour le maintien de la continuité de session. Pour résoudre ce problème, nous avons proposé le PMIP-MIVH, une approche basée sur le protocole PMIP et qui profite des avantages de l'utilisation d'une interface logique dans le traitement du transfert vertical intercellulaire. Pour améliorer et étendre notre approche, nous avons également proposée une méthode transversale (multi-niveaux) de sélection du meilleur réseau disponible, basée sur la logique floue. Les résultats analytiques et les résultats de simulations montrent tous que les solutions proposées sont performantes comparées aux autres méthodes de transfert existantes et qu'elles améliorent efficacement la gestion de la mobilité dans les réseaux véhiculaires.

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Contents

List of Figures

List of Tables

List of Algorithms

Acronyms

μIP Micro Internet Protocol

6LoWPAN IPv6 over Low Power Wireless Personal Area Network

AAA Authentication, Authorization and Accounting

ABC Always, Anytime, Anywhere Best Connection

AHP Analytic Hierarchy Process

ANDSF Access Network Discovery and Selection Function

AP Access Point

BBST Balanced Binary Search Tree

BCE Binding Cache

BS Base Station

BSS Basic Service Set

C-ITS Cooperative Intelligent Transport Systems

CALM Continuous communications for vehicles[22]

CALM-SL CALM Service Layer [22]

CAM Cooperative Awareness Message

CoAP Constraint Application Protocol [23]

CRUD Create, Read, Update, Delete

D2D Device-to-Device

DD-PMIP Data Driven Distributed-PMIP

DENM Decentralized Notification Message

DMM Distributed Mobility Management

DSRC Dedicated Short Range Communications

E-UTRAN Evolved UMTS Terrestrial Radio Access Network

EPC Evolved Packet Core

ePDG Evolved Packet Data Gateway

ETSI European Telecomunication Standards Institute

FDMM Fully Distributed Mobility Management

FIS Fuzzy Inference System

FLC Fuzzy Logic Controllers

GTP GPRS Tunneling Protocol

HA Home Agent

HNP Home Network Prefix

HoA Home Address

HSM Hardware Security Management

HSS Home Subscriber Server

HTTP REST HyperText Transfer Protocol Representational State Transfer

HVN Heterogeneous Vehicular Networks

IEEE Institute of Electrical and Electronics Engineers

IETF Internet Engineering Task Force

IoT Internet of Things

IoV Internet of Vehicles

IP Internet Protocol

ITS Intelligent Transportation Systems

LDM Local Dynamic Map

LLAP Lightweight Local Automation Protocol

LMA Local Mobility Anchor

LoRaWAN Low Power WAN

LTE Long Term Evolution

M2M Machine-to-Machine

MAAR Mobile Anchor and Access Router

MADM Multiple Attribute Decision Making

MAG Mobile Access Gateway

MANET Mobile Ad-hoc Networks

MCDM Multiple Criteria Decision Making

MCM Multi-Connection Manager

MIH Media Independent Handover

MIPv4 Mobile IPv4

MIPv6 Mobile IPv6

MIVH Mobile Internal Vertical Handover

MLA Multi-Link Adaptor

MME Mobility Management Entity

MN Mobile Node

MQTT Message Queuing Telemetric Transport [24]

NAS Non Access Stratum

NEMO Network Mobility

NS3 Network simulator 3

OBU On-Board Unit

OCB outside of the Context of BSS

OMA-DM Open Mobile Alliance Device Management [25]

OSI Open Systems Interconnection model

OTrP Open Trust Protocol

PBA Proxy Binding Acknowledgement

PBQ Proxy Binding Query

PBU Proxy Binding Update

PDMM Partial Distributed Mobility Management

PDR Packet Delivery Ratio

PGW Packet Data Network (PDN) Gateway

PLMN Public Land Mobile Network

PMIP-LR PMIP-Localized Routing

PMIP-MIVH PMIP-based Mobile Internal Vertical Handover

PMIPv6 Proxy MIPv6

PQA Proxy Query Acknowledgement

QoS Quality of Service

RAT Radio Access Technology

RB Resource Blocks

RE Resource Element

RFC Request For Comments

ROLL Routing overlow Power and Lossy Networks

RPL Routing Protocol Low Power and Lossy Networks

RRC Radio Resource Control

RSEL RSU selection

RSRP Reference Signal Received Power

RSRQ Reference Signal Received Quality

RSSI Received Signal Strength Indication

RSU RoadSide Unit

RTT Round-Trip Delay Time

S-IC Security Information Connector

S-MIB Security Management Information Base

S-PMIP Signal-Driven PMIP

SAE System Architecture Evolution

SD-PMIP Signal-Driven Distributed PMIP

SDN Software Defined Network

SGW Serving Gateway

TS Technical Specification

UE User Equipment

UX User Experience

V2I Vehicle-to-Infrastructure

V2V Vehicle-to-Vehicle

V2X Vehicle-to-Everything

VANETs Vehicular Ad-hoc NETworks

WAVE Wireless Access in Vehicular Environments

WHO World Health Organization

Wi-Fi Wireless Fidelity

WLAN Wireless Local Area Network

XMPP eXtensible Messaging and Presents Protocol

Chapter 1
Introduction

1.1. Context

Over the past years, road safety has become an important issue on which many organizations have devoted their attention. Later in December 2018, statistics of the World Health Organization (WHO) have shown that around 1.35 million of road accidents' deaths occured yearly worldwide [1, 2]. Accordingly, these road accidents were the first cause of death of youngs (5-29 old). The alarming sign was that 90% of those accidents were due to driver's errors. Fortunately, since some decades ago, the evolution of the internet continues to revolutionize many aspects of human life. It started by connecting computers, then smartphones, before it becomes generalized to connecting everything which gives birth to the Internet of Things (IoT) paradigm. In order to alleviate these road safety issues and thanks to the telecommunication and technologies' advancements, vehicles are now able to have internet access and communications capabilities. Those are the facts that have motivated the introduction of Intelligent Transportation Systems (ITS) and Vehicular Ad hoc Networks (VANETs). The Internet of Vehicles (IoV) is, therefore, an evolution of VANETs where IoT is applied and in which the main component is the vehicle.

Added to the many opportunities that IoV presents, there are still many challenges and issues that must be considered with great attention. One of them is the maintenance of a continuous connectivity in order to provide an Always, Anytime, Anywhere Best Connection (ABC) environment that is required for the autonomous vehicle deployment.

1.2. Problematic

VANETs are emerging networks that connect vehicles with each others using the On-Board Units (OBU) and with the road infrastructure such as the RoadSide Units (RSU). They allow to implement safety applications (collision avoidance, works alerts, etc.), real-time applications (autonomous driving), intelligent transportation systems applications (traffic management, detour proposal, etc.) and comfort applications (automatic toll payment, connecting to the online media, etc.). Vehicle needs a near-continuous connection to work properly. However, two of the most important characteristics of VANETs, which are their high mobility and their frequent dynamic topology changes, are critical since they generate scattered networks. Therefore, VANETs need a high coverage density in order to work efficiently. Unfortunately, the deployment of the Dedicated Short Range Communications (DSRC), which is the VANETs' communications standard will take time, especially for the infrastructure due to its expensive cost which is estimated to €660 Millions from 2020 to 2026 [3, 4]. It is intuitive to use other available networks in the vehicle such as passengers' mobile phones networks, in addition to the IEEE 802.11p vehicular network. The cellular network (3G, LTE, 4G) is the best alternative candidate thanks to its wide deployment and accessibility (in general, smartphones are available in most vehicles). This is achievable by using the concept of Heterogeneous Vehicular Networks (HVNs) which consists in the hybridation of vehicular network (IEEE 802.11p) and cellular networks. However, HVNs require the development of efficient handover management mechanisms, allowing the vehicle to fastly and efficiently switch among the available communication technologies at any time.

1.3. Motivation and objectives

Our main motivation was then, to propose a mechanism that helps in the establishment of a continuous connection and which maximazes the vehicular communication.

Hence, our main objectives during this thesis are:

- to reduce the handover latency, thus handover delay reduction
- to decrease and possibly to avoid the packetloss as it is given by the formula $\Rightarrow packetloss = datarate * time$. Therefore, the reduction of handover delay implies the reduction of packetloss.
- to propose a handover algorithm that selects the best network candidate
- to avoid the effect of ping-pong in handovers.

1.4. Contributions

In this thesis, we propose three contributions in order to achieve our main goal of establishing a continuous connectivity in the vehicular networks.

The first contribution is the proposition and design of a vertical handover mechanism denoted PMIP-based Mobile Internal Vertical Handover (PMIP-MIVH), which uses a logical interface and a distributed PMIPv6 scheme in order to improve the handover performance and consequently the overall network's performance.

The second contribution is the proposition of a fuzzy logic-based algorithm for selecting the best network to hand the vehicle over when one network becomes weak/down while there are other networks which are available.

The third contribution is the implementation of the above proposed solutions in the well known Network Simulator NS3 in order to test these solutions in more realistic scenario. For that, we have extended the implementation of the PMIPv6 standard in NS3. Then, we have also integrated a fuzzy library in the NS3 simulator. Furthermore, we have implemented a server-like feature that helps in the data collection phase of the handover. This feature allows storing measurements' reports data of all available networks, for a future usage of them in the decision phase of the handover algorithm.

In this thesis, 3 publications were made:

1. Livinus Tuyisenge, Marwane Ayaida, Samir Tohme, Lissan-Eddine AFILAL. *"Network Architectures in Internet of Vehicles (IoV): Review, Protocols Analysis, Challenges and Issues"*. In: International Conference on Internet of Vehicle (IoV). Springer. 2018, pp. 3–13

2. Livinus Tuyisenge, Marwane Ayaida, Samir Tohme, Lissan-Eddine AFILAL. *"Handover Mechanisms in Internet of vehicles (IoV): survey, Trends, Challenges, and Issues"*. In: Global Advancements in Connected and Intelligent Mobility: Emerging Research and opportunities, 2019 IGI Global. pp. 1–64

3. Livinus Tuyisenge, Marwane Ayaida, Samir Tohme, Lissan-Eddine AFILAL. *"A Soft Logical Interface PMIPv6-based Handover Mechanism in VANETs"*. In: Global Communications Conference (GLOBECOM), 2019 IEEE. pp. 47–55
   A fourth publication is in a minor revision process at the time of writing this thesis:

4. Livinus Tuyisenge, Marwane Ayaida, Samir Tohme, Lissan-Eddine AFILAL. *"A Mobile Internal Vertical Handover Mechanism for Distributed*

Mobility Management in VANETs". Submitted for publication in: Journal of Vehicular Communications, 2019 Elsevier

1.5. Thesis outline

This thesis is organized as follows: first of all, in chapter 2, we will start with an overview of the communication types between vehicles in section 2.1, then we will present the IoV architectures in section 2.2, and we will see the basic handover operations in section 2.3. We will describe the handover phases in section 2.4. After that, we will propose our classification of handover types in section 2.5, followed by their description. A highlight on network-based approaches and Distributed Mobility Management (DMM) will be made in section 2.5.3.2 and section 2.5.5.2 respectively, since our proposed solutions will be based on them.

Then, in the chapter 3, after noting the benefits of cellular networks, including their coverage and availability around the world, and given the constraints of continuous connectivity imposed by vehicular networks, we have found it relevant to study and to integrate the LTE technology into our works. This is why we devoted this chapter to the study of handover protocols and handover algorithms used in heterogeneous networks including LTE. Thus, we will start by an overview of the handover protocols in LTE networks in section 3.1, in which we will also discuss the seamless vertical handover enablers: the MIH and the ANDSF in section 3.1.1, followed by the PMIPv6 support in LTE in section 3.1.2. Then, the required enhancements of LTE, in order to support V2X services, will be given in section 3.2. Then after, for the understanding of the methods that we used in our proposed solutions, we dedicated a section 3.3 in which we will see the concept of the Multiple Attribute Decision-Making (MADM) in section 3.3.1,the Analytic Hierarchy Process (AHP) method in section 3.3.2, and the Fuzzy Logic Controllers (FLC) in section 3.3.3. Then, in chapter 4, we will describe our proposed Mobile Internal Vertical Handover (PMIP-MIVH) approach in section 4.1. We will present an application use-case of our approach in section 4.2. Then, we will propose an analytical model of our approach in section 4.3 and we will discuss the analytical results for our PMIP-MIVH approach in section 4.4.

In chapter 5, we will propose two types of algorithms of selecting the best network candidate. Thus, we will start by an AHP-based method proposition in section 5.1. Then, in section 5.2, we will define our expected QoS metric by proposing a tradeoff function between the application requirements and the service offered by each available network, before using it in the Fuzzy Inference System (FIS) in section 5.3.

Then, in chapter 6, we will see in details the implementation steps in section 6.1, simulation results of PMIP-MIVH will be discussed in section 6.2 and the simulation using the proposed fuzzy logic-based algorithm will be given in section 6.3. Finally we will conclude in chapter 7.

Chapter 2
Background

Before talking about how handovers are achieved in VANETs, we will start by describing how the VANETs communications work in section 2.1, then, we will explore in section 2.2, some existing novel IoV architecture solutions on which the IoV deployment might be based. After that, we will give an overview of the basic handover operations in section 2.3. Then, we will see the vertical handover phases in section 2.4. At the end of this chapter, we will propose our classification and description of the existing handover methods in section 2.5.

2.1. Description of Vehicular Ad-hoc Networks

VANETs are emerging networks that consist in a particular category of Mobile Ad-hoc Networks (MANETs) category, in which the main component node becomes the vehicle. However, VANETs (or the IoV) ecosystem cooperates with other different Cooperative Intelligent Transportation System (C-ITS) components. Among them, there is the road infrastructure which is composed of RSUs, that are connected to the traffic management center through a central ITS station (ITS-C). In Europe, all the ITS stations are based on the European Telecommunications Standards Institute (ETSI) ITS communication stack, represented by figure 2.1. RSUs (also called ITS-R) and vehicles (also called ITS-V) communicate through wireless networks based on ITS-G5 network (based on IEEE 802.11p standard). Thus, the main types of communications in VANETs are:

- Vehicle-to-Vehicle (V2V),
- Vehicle-to-Infrastructure (V2I)
- Vehicle-to-Network (V2N)
- Vehicle-to-Pedestrian (V2P)
- Vehicle-to-Sensors (V2S)
- Vehicle-to-Grid (V2G)

- Vehicle-to-Everything (V2X), and recently
- Cellular-V2X (C-V2X)

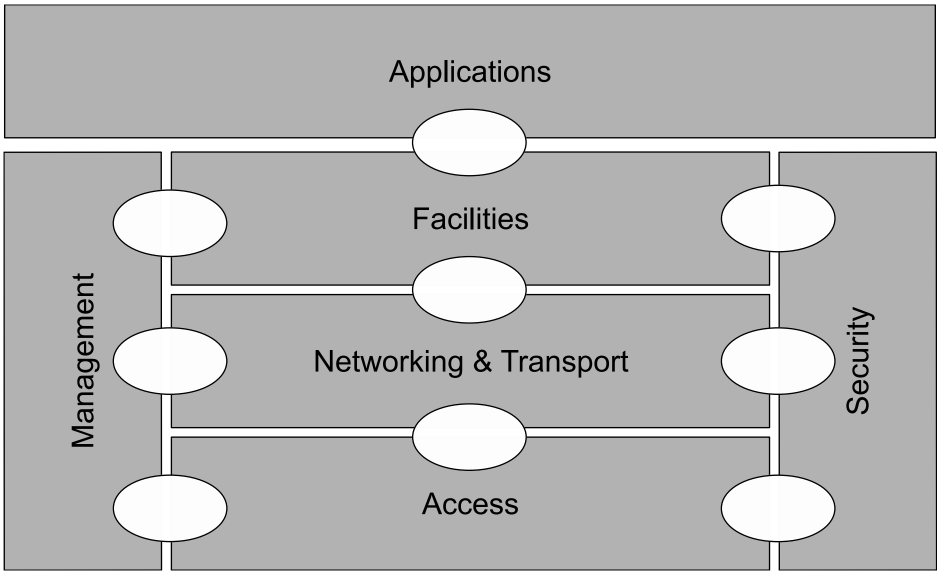


Figure 2.1 – Architecture of the ETSI ITS stack.

As it can be seen in figure 2.1, the traditional TCP/IP or OSI model has been extended and includes:

- a facilities layer which is responsible for VANETs related application messages (Cooperative Awareness Message (CAM), Decentralized Notification Message (DENM), Local Dynamic Map (LDM)) and communications process.
- The combination of Network and Transport layer in one layer.
- Integration of two special layers : one for Management and another for Security.
- The presence of ITS dedicated stack which integrates the GeoNetworking addressing and routing protocol [26].

Hence, the functionnalities of this ETSI ITS stack are as follows:

- Access layer corresponds to the Physical and Data Link layers from the OSI stack (i.e. an Ethernet layer using the *EtherType 0x8947* on a 5.9 GHz band [27]);

- GeoNetworking corresponds to the Network layer from the OSI stack, where we define the routing method of the packet,

- Payload, which is optional and corresponds to the Transport and Session layer (with the Basic Transport Protocol), the Presentation and Application layer (with the payload encoding) and the Facilities layer. Two main comunication message are used in the VANETs, thanks to this facilities layer. There are:

  – Cooperative Awareness Messages (CAM) [28] which periodically gives vehicle information and positions to all neighbor stations located within a single hop distance.

  – Decentralized Environmental Notification Messages (DENM) [29], which are mainly used by the Cooperative Road Hazard Warning (RHW) application in order to send information about particular events (as accidents, heavy raining, ...)

- Application layer is related to usual applications embedded by ITS components. We can cite as example:

  – In-vehicle signaling, which shows driving head, static signaling, dynamics of speed.

  – Vehicle data collection (such as its position, speed, direction), road event data input manually by driver (animal on the road, works alerts, etc.), automatic warning data (impact, emergency brake, ...)

  – Information about the road traffic: traffic light color, journey time, recommended route, access to services...

  – Road hazard signaling, unexpected and dangerous events which represent the alerts from the European directive (temporary slippery road, pedestrian on the road, reduced visibility, ...)

  – Parks relay and multi modal system: location and availability of parking relays, schedules of public transportation.

In order to see the importance of these layers, especially when designing an efficient vertical handover, we are going to see other novel variants of this architecture that have been proposed in the IoV litterature. After that, we will see the handover concept.

2.2. IoV architectures

The high level of mobility and the dynamic change in the topology, which most characterize vehicular networks (i.e VANETS), make the deployment of connected vehicles and applications very challenging. However, the large and very fast development of telecommunications systems, and more recently, the deployment of IoT (Internet of Things) allow a significant contribution in this field and actually many communication systems are developed.

This has encouraged the development of the novel concept of IoV (Internet of Vehicles) [30]. By analyzing the communications possibilities offered by the IoV ecosystem, it results that IoV has 6 components which are: Vehicle (V), Person (P), personal devices (D), network Infrastructure (I), Sensing device (S) and Roadside device (R) as described in [31]. This fact has also made these communications in IoV very complex. Thus, efficient and reliable network architectures should be provided in order to have efficient IoV deployment. That is, several IoV communication architectures were proposed and are mostly layer-based, as it is in the traditional architectures (OSI,TCP/IP,ETSI). It is why, in this thesis, we highly consider the cross-layer based handovers as it will be detailed in section 2.5.

However, when considering cross-layer approach, as described by the authors of [31], some challenges have to be taken into account in a layered design architecture. The main ones are: the optimal number of layers and the capabilities for each layer including:

- network characteristics: such as interoperability, scalability, reliability, modularity, etc. More details and description of these issues can be found in [32],
- communication technologies: such as Wi-Fi, Bluetooth, Zigbee, 4G/LTE, etc.
- data security: such as confidentiality, integrity, availability, authentication and identification, etc.
- user interaction: such as visual, haptic, audio, etc.

For our study, we are focusing on the first 2 main challenges in order to ensure efficient communications, based on vertical cross-layer handover approaches, especially for the V2I, V2R, V2P communications. Several issues that we highly recommend to consider when designing a vertical cross-layer handover includes:

- interconnecting devices to heterogeneous networks,

- flexible adaptation to new technologies,
- handover latency
- packet loss
- Internet integration, service-oriented architecture,
- plug-and-play-based interface (technology agnostic).
- Quality of Service (QoS) and
- User experience (UX)

In order to clarify the interactions between vehicles and external devices that are involved in the IoV communication (such as in handover for our use-case), some novel interaction architectures have been recently proposed in the litterature. This gave hope to the IoV deployment possibility despite the RSU deployment delay since its expensive implementation of road infrastructure (i.e. RSUs), which is estimated to €660 Millions from 2020 to 2026 [3]. Thus, in [33], Bonomi from Cisco has proposed and described a 4 layers-based architecture as shown in figure 2.2. He proposed to consider the 4

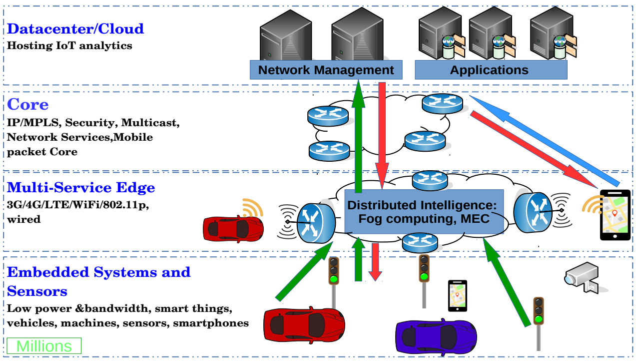


Figure 2.2 – IoV 4 layers architecture based on [33]

steps that every IoV communication always involves which are: Embedded Systems and Sensors, Multi Service Edge, Core, Data Center and Cloud, as it can be seen in this figure 2.2. A similar cloud-fog-edge architecture for IoT is presented in [32] where authors considered 3 layers which are: IoT, Fog and Cloud.

In [34], authors also proposed a 5 layered architecture, illustrated by figure 2.3, which is composed of the following layers:

- Perception: this layer represents the interaction between the vehicle and its environment. It uses the devices present inside the vehicle such as sensors, actuators, personal devices and those installed across the road such as RSU, in order to gather relevant information to be used in vehicle's decisions.
- Coordination: this layer is mainly responsible of the system's interoperability, routing and messages' transportation security.
- Artificial intelligence: this is the core layer, where decisions component tasks have to be executed. This layer mainly focuses on big data analysis, data mining, Cloud computing and expert systems based decision.
- Application: this layer concerns the kind of services and requirements available in the system.
- Business: it is the part that describes which kind of businesses the IoV market will offer to users.

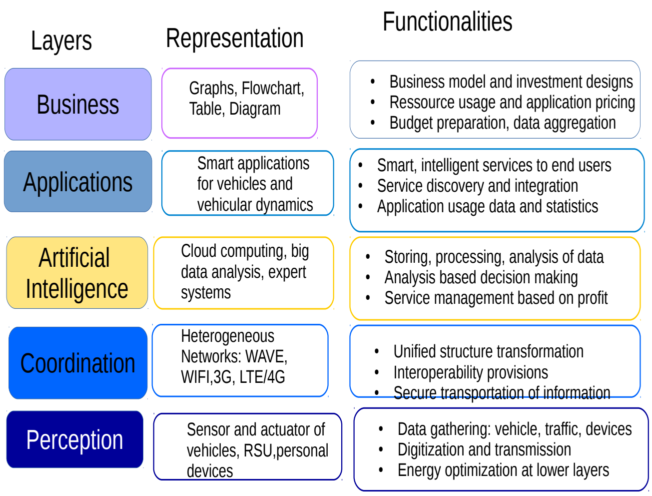


Figure 2.3 – IoV 5 layers architecture based on [34]

Other researchers such as in [35, 36, 37, 38] proposed their contributions in IoV architectures that we decided to summarize in the table 2.1 for comparison and good readability. In order to propose a robust routing protocol for IoV environment, authors of [39] have extended these architectures presented in previous works, by integrating the Software Defined Networks (SDN) paradigm which consists in separating the network traffic control plane and the data transfer plane. Therefore, they proposed an architecture with 6 layers which are: Perception layer, communication layer, application layer, cost layer, security layer, and a layer for law, ethic, private life and legal use. Then, they applied the SDN paradigm in the communication layer in which they specified a SDN routing protocol (Control plane + Data plane) sub-layer and a Radio Access Technologies (RAT) types (homogenous or heterogenous) sub-layer.

In [31], authors proposed a 7 layers-based architecture, shown in figure 2.4. They designed this 7 layers-based architecture by reducing the complexity of layers' functionalities. Thus, they grouped the more similar functions in a same apropriate layer, hence, making its implementation easy.

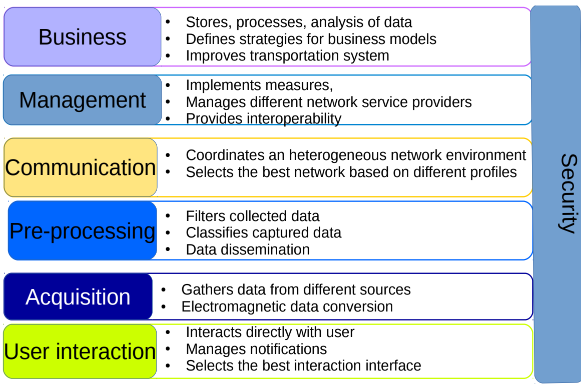


Figure 2.4 – IoV 7 layers architecture based on [31]

We must recall that the main objective of layered architecture is the optimization of the number of layers by enhancing the differentiability among layers. This optimization must be also deployed as more efficiently as possible in order to achieve the network characteristics and requirements, which are mainly: interoperability, reliability, scalability, modularity, simplicity and integration flexibility with the internet. In other words, a service oriented architecture, based on the respect of the QoS, the QoE, the user preferences, and plug-and-play interfaces. Therefore, as illustrated in figure 2.4, they proposed a layer for user interaction, which directly exchanges with the user interface, a layer for data acquisition, a pre-processing layer in which the collected data must be pre-processed before being used in the next layer which is the communication layer. This latter coordinates the heterogenous network environment. After that, they include a layer for interoperability and network service providers, which is called Management. Finally, they proposed a business layer and a security related layer.

They also introduced a Device-to-Device (D2D) communication approach, which might be a promising and probably one of the most used solutions in the next years to come in the Machine-to-Machine (M2M) communications context. A thoroughly and exhaustive review on the Device-to-Device communications can be found in [36]. The D2D architecture approach in IoV is illustrated by figure 2.5.

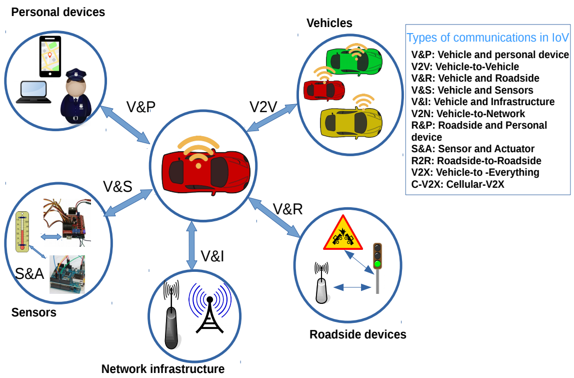


Figure 2.5 – Different types of D2D communications in IoV based on [31]

Considering the challenging problem towards resource allocation to guarantee Real-Time (RT) traffic in IoV and to enhance the resource utilization efficiency, authors of [38], not only specified an IoV architecture, but, they also proposed a model for resource allocation and optimization by following the supply and demand approach and utility function. Their proposed architecture is an hierarchical IoV architecture that consists of three layers, which are: a data-gathering Cloud, an internet-access Cloud, application Cloud. In their architecture, they also considered four networks which are: the On-Vehicle-Sensor(OVS) network, Vehicle-to-Vehicle (V2V) network, Vehicle-to-Infrastructure beside road (V2I) network and a Vehicle-to-People (V2P) network. In the same direction of real-time challenges, authors of [40] proposed a fog computing Real-time Based ITS Big Data Analytics (RITS-BDA) architecture in the IoV environments, which is composed of a three dimension system architecture including the dimensions of IoV, intelligent computing and real-time big data analytics. RITS-BDA is, then, a multi-dimensional layered architecture which is made of the following layers: 4 layers in the intelligent computing dimension (3 hierachical Fog computing layers, Cloud computing layer), 3 layers for the real-time big data analytics dimension (serving layer, batch layer, speed layer) and 5 layers for the IoV dimension (Perception layer, Infrastructure network layer, Communication layer, Application layer, Business layer). Their architecture aims to serve the real implementation of real-time ITS big data applications and is extended from a generic real-time big data processing architecture called lambda architecture that was introduced in [41]. For more information about these big-data and analytics based architectures, readers are refered to the respective following articles: [40, 41, 32].

Therefore, we summarized in the table 2.1, the existing IoV novel architecture solutions that we found in the litterature.

Table 2.1 – Summary of IoV layers architecture solutions

IoV architectures with	**Names of layers**	**Communication models supported**	**Security**	**work**
3 layers	client, connection, cloud	V2V, V&R, V&P, V&I	Security as a service	[35]
3 layers	vehicle, location, cloud	V2V, V&R	Cross-layered	[37]
3 layers	a data-gathering cloud, an internet-access cloud, application cloud	OVS, V2V, V2I, V2P	not specified	[38]
3 layers	D2D area network, network management, D2D applications	D2D-B, D2D-C, D2D-D, M2M-D and D2D-N	Not specified	[36]
4 layers	services, operation, infrastructure, end points	V2V, V&I	Cross-layered	[33]
5 layers	perception, coordination, artificial intelligence (AI), application, business	V&I, V2V, V&S, V&P, V&R	Security plane	[34]
6 layers	perception, communication, application, Cost, Security, legal, ethical use	V2V, V&I, V2X	Security plane	[39]
7 layers	User interaction, Acquisition, preprocessing, communication, management, Business, security	V&I, V2V, V&S, V&P, V&R, R&P, R2R, S&A	Cross-layered	[31]
Multi-dimensional: 13 layers	Perception, Fog computing (3 tiers), cloud computing, serving, batch, speed, Infrastructure network, AI, Communication, Application, Business	V&I, V2V, V&S, V&P, V&R, R&P, R2R, S&A, V2X	Cross-layered	[40]

where: D2D-B represents Backhaul applications , D2D-C is for critical application , D2D-D stands for direct D2D, M2M-D: direct M2M and D2D-N represents the non-critical applications.

Thus, in the following section, we made an analysis of the protocols' stack of these IoV network architectures, in order to show some advancements that need to be taken into account in the IoV standardization activities.

Analysis of the IoV protocols' stack and IoV architectures

For each architecture, a protocol stack is proposed. It consists of specification of the functional requirements of each architecture layer by organizing the apropriate existing protocols such as VANETs standards, IEEE, ETSI, 3GPP standards, etc. For the 5 layers architecture in [34], authors proposed a protocol stack (ilustrated by figure 2.6) composed by 4 planes which are:

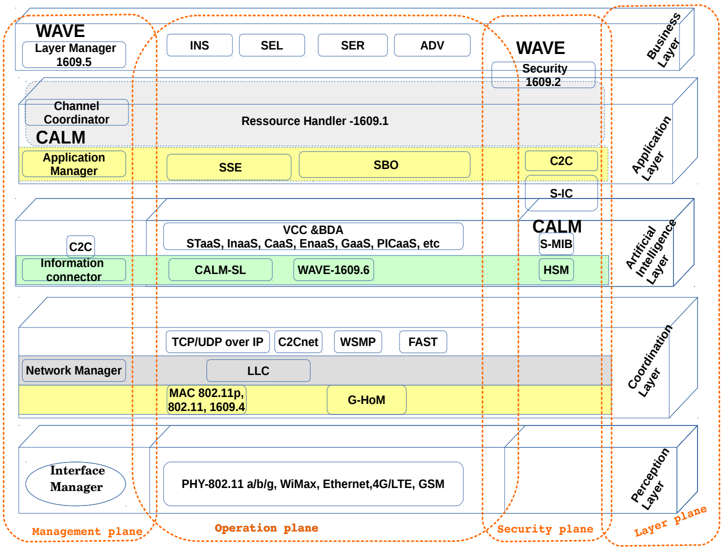


Figure 2.6 – Protocol stack of the IoV architecture with 5 layers based on [34]

management plane, operation plane, security plane and layer plane. However, Authors of [31] proposed a protocol stack of two plane: an operational plane and a security plane as illustrated by figure 2.7, where the use of the following protocols is illustrated: CALM Service Layer [22] (CALM-SL), Open Mobile Alliance Device Management [25] (OMA-DM), IPv6 over Low Power Wireless Personal Area Network (6LoWPAN), Routing Protocol Low Power and Lossy Networks (RPL), Micro Internet Protocol (μIP), Routing overlow Power and Lossy Networks (ROLL),eXtensible Messaging and Presents Protocol (XMPP), Constraint Application Protocol [23] (CoAP), HyperText Transfer Protocol Representational State Transfer (HTTP REST), Message Queuing Telemetric Transport [24] (MQTT), Lightweight Local Automation Protocol (LLAP), Low Power WAN (LoRaWAN), Open Trust Protocol (OTrP), Security Management Information Base (S-MIB), Hardware Security Management (HSM), Security Information Connector (S-IC). A review of the use of these protocols in IoT is available in [32].

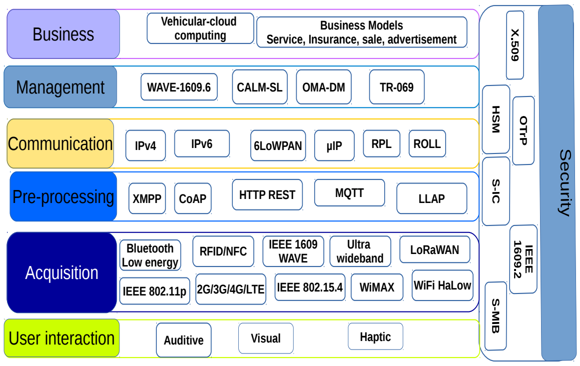


Figure 2.7 – IoV protocol stack with 7 layers based on [31]

It is to be noticed that each plane interacts with all the layers in its respective architecture. For more details about protocol stack functionalities and description, readers are encouraged to refer to the corresponding articles in [34, 31].

By analyzing these aforementioned proposed architectures in IoV domain, we found many aspects that proved that the IoV is still in its early stage of standardization and presents many opportunities and challenges for both academia and industries researchers, IT engineers, internet services providers, etc. This is remarkable especially when considering the IoV perception from different studies, whether it is from industrial or academic researchers. The considered point of view used to propose and design these architectures are completely different and sometimes there is interchangeability between layers. For examples:

- In figure 2.3, the perception layer (L1) functionnalities corresponds to the functionnalities presented in embedded systems and sensors layer (L1) in figure 2.2. The same layer is split into two layers (i.e. user interaction (L1) and acquisition (L2)) in figure 2.4.
- coordination layer (L2) in figure 2.3 is called multi-service edge (L2) in figure 2.2, whereas it is called communication layer (L4) in figure 2.4.
- data center/cloud layer (L4) in figure 2.2 is divided into 3 layers (artificial intelligence layer (L3), application layer (L4), business layer (L5)) in figure 2.3, while it is divided into 2 layers (Management layer (L5) and Business layer (L6)) in figure 2.4.

We can also remark an issue in layer's order between figure 2.4 and figure 2.3. In figure 2.4, there is a pre-processing layer, which corresponds to artificial intelligence in figure 2.3, before the communication layer. However, in figure 2.3, the processing which takes place in the artificial intelligence layer comes after the coordination layer. From this study, we noticed that a good handover algorithm might consider as much as possible a lot of amount of information, collected from different environment and from these different layers above-mentionned. Another aspect to be considered is the presence of a security dedicated layer in figure 2.2 which was not available in the 5 layers based architecture in figure 2.3. From that, we also noticed that the interoperability might be highly considered when designing handover algorithm, since there are many different IoV architectures that are actually proposed. The comparison may be long when comparing these architectures one by one, from a 3 layers based architecture to a 13 layers based architecture. It is why we preferred to make it briefly by establishing the table 2.1. Hence, all those aforementionned aspects show the earlyness stage of the IoV standardization which means that there still be a lot of challenges and research' opportunities in this field. One of them still the mobility management in heterogeneous vehicle network. This is why we will focus, in the rest of this thesis, on the handover mechanisms.

2.3. Basic operations of handover

Generally speaking, the term *handover (or handoff)* refers to the fact of transfering an ongoing call or data session from one *Point of Attachment (PoA)* to another *without service disruption* (figure 2.8).

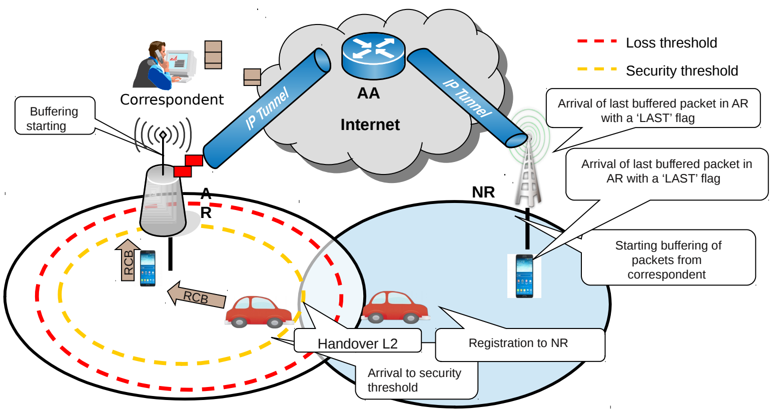


Figure 2.8 – General mechanism of handover

As illustrated by figure 2.8, when a vehicle (mobile) had a communication session in a given network and that it moves away from that network, a special mechanism must be taken into account in order to maintain the communication which was already in place. In order to do that, an anticipation must be done. Reason why on the figure 2.8, two regions are drawn: the security region delimited by the security threshold (yellow) and the loss region delimited by the loss threshold (red). This means that, when the vehicle arrives at the first zone (security threshold zone), it stills connected to the previous Access Router (AR), also called source router and must prepare itself for a handover by starting the handover at the second layer (Handover L2). The second zone expresses the region from which the vehicle might lose almost its destined packets if it had not yet been well connected to the next router (NR) or if no packet buffering is in place. Generally, the previous access router is referred to as source access router (in the source network) while the next router is referred to as the target router (in the target network). This process is called *handover*. It has to be as fast as possible in order to have an acceptable and efficient service. When a handover occurs within the domain of a single Radio Access Technology (RAT), which means that both the source and target networks use the same RAT, the process is known as horizontal handover. In contrast, vertical handover is a term that refers to handover among heterogeneous wireless access network technologies as in our case of Heterogeneous Vehicular Networks (HVNs).

However, *the most critical issue is founding and fixing these two above mentionned thresholds (security and loss threshold) which take place in the decision phase of the handover. We will tackle this throughout the whole rest of this thesis, especially in section 2.4 and section 3.3.* Before that, let us see the main phases that are involved in the vertical handover process.

2.4. Vertical handover phases

Three steps are necessary in order to handle a vertical handover in heterogeneous networks. As illustrated by figure 2.9, these steps are:

1. Handover Information Gathering Phase
2. Handover Decision Phase
3. Handover Execution Phase

At the first step (Handover Information Gathering phase), the vehicle discovers other networks that are available in its vicinity and to which it

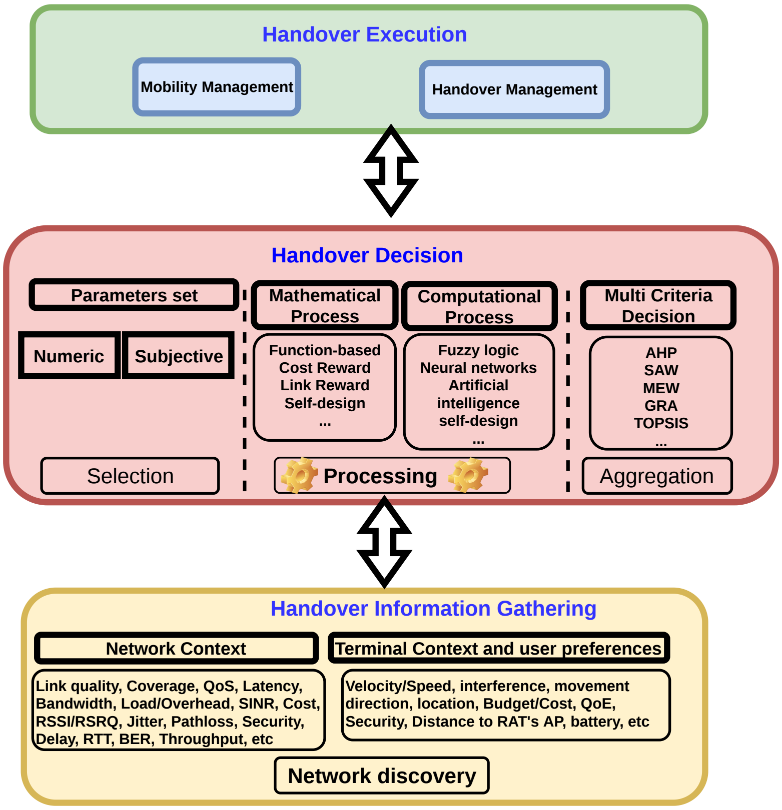


Figure 2.9 – handover main phases

can connect. The vehicle may detect the presence of these networks in two ways: passive way or active way. In passive way, the mobile receives beacons (HELLO messages) and evaluates the information contained inside each beacon. Therefore, it detects which networks that are available, along with their characteristics. In the active way, the vehicle also broadcasts messages called probe messages in addition to receiving the HELLO messages. During this phase, the vehicle collects all the parameters that are necessary in order to decide on which available network it can connect. The Media Independent Handover (MIH) [42], described in section 3.1.1, is often used in order to handle this phase. We will base our proposed PMIP-MIVH approach (section 4.1) on it, especially for the signaling and initiation part of the handover process. However, there is no standard specification on how this phase must be achieved since there is no standard specifying which parameters, neither the amount of parameters that must be considered.

As illustrated by figure 2.10, the collected data might be:

- In-vehicle data extracted from sensors that are embedded inside the vehicle
- Outside the vehicle data such as environment conditions data, neighbouring topology changes, etc.

Morever, some of this data are static (e.g. beacon reception interval, available bandwidth, channel frequency and channel number, transmission range, transmission power, etc.), while other data parameters data are very dynamic (e.g. velocity, RSSI). Readers can find more details and classification of these parameters in [13, 43, 44]. Figure 2.10 shows a classification of parameters that we considered as very important for the handover decision phase in VANETs.

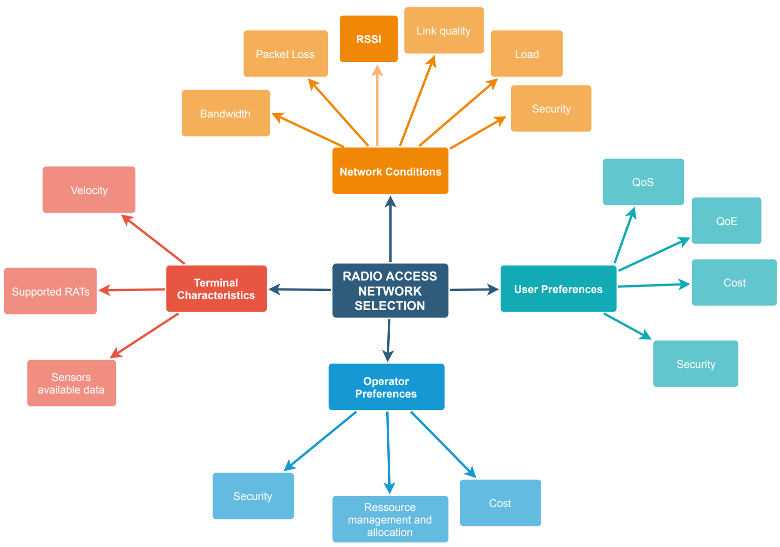


Figure 2.10 – Classification of main parameters for a handover

In the second phase (Handover Decision Phase), data from the selected parameters sets (selection) must be processed (processing) using different methods such as those mentionned in figure 2.9. When many candidate networks (also refered as alternatives) are available, these processed data must be aggregated and scored in order to rank these candidates. This is the most critical process of a vertical handover, since again, there is no standardization proposed for this phase. Better saying, this phase is in charge of the decision of *When* and *Where* to trigger the handover in order to make the vehicle *Always Best Connected (ABC), Any time, Any where*. The *When* decision refers to the precise instant in time (vehicle's arrival time at the security threshold in figure 2.8) to make an optimal handover, while the

Where refers to selecting the best network fulfilling our requirements for the switching. **This also implies to estimate the required minimum overlapping distance between the previous network and the best network**. It stills an open research opportunity, which also means that there is many different methods proposed in the litterature for handling this phase. Thus, we have dedicated a special overview on these methods in section 3.3 by focusing on the Multiple Attribute Decision-Making (MADM) methods, the Analytic Hierarchy Process (AHP) and fuzzy logic that we used in our works in this thesis. At the end of this process, the best candidate is chosen and the third handover phase which is the handover execution is triggered.

The execution phase is in charge and responsible of committing the vertical handover (VHO) itself and triggering a network binding update. With this purpose, this handover execution phase is mostly concerned with control, security, session and mobility, among other issues in order to perform a seamless handover. Therefore, the third phase is composed of two main process: the handover management and the mobility management.

In the **handover management**, an entity in-charge of controlling the VHO process (i.e. mobile in mobile controlled VHO or network in network controlled VHO as it will be detailed in section 2.5.3), executes procedures to manage the connections. These procedures usually perform Registration, Association, Re-association, and Dissociation tasks.

The **mobility management** is one of the key issues of the seamless handover concept. It is ensured by few standard protocols that are proposed for maintining the session alive (such as MIPv4, MIPv6, SIP, HIP, NEMO, PMIPv6,etc). Some of these protocols will be described in section 2.5. There are also many reviews on the mobility management in the litterature [13, 45, 46].

Mobility management is generally achieved by asking the mobile node or a mobile access gateway (MAG) to send binding updates (BUs) to its home agent (HA) every time it moves from a network to another (visited network).

Meantimes, the mobile node may send data packets via its home agent immediately after sending the binding update, but the home agent will not be able to route traffic back to the mobile node before it receives the binding update. This incurs, at least, a half of the round-trip delay time (RTT), before packets are again forwarded to the right place. However, if the mobile node chooses to wait for a binding acknowledgement (BA), an additional delay for sending data packets will be incurred. Note that, depending on location of the home agent and its distance to the mobile, the RTT can be relatively long, especially when they are in different parts of the world. This will therefore increase the handover latency, which subsequently may result in the mobile application's performance degradation.

In order to handle this mobility issues, 3 main functions have been defined [47], especially for centralized mobility management approaches. These functions are:

- Anchoring Function (AF): it is responsible of IP address allocation to a mobile node. This address may be a Home Address (HoA) at the home network, a core of address (CoA) which is given from the visited network or a home network prefix (HNP), topologically anchored by the advertising node. This means that the anchor node will be able to advertise a connected route for the allocated IP prefixes into the routing infrastructure, which implies that the anchor node have to store the IP address mapping in his local routing table known as binding cache table. This function is a control-plane function. Note that default address selection is specified in RFC 6724 [48] for IPv6. However, due to the growth of connected devices that require an IP address assignement and especially an IPv6 address, there is a promising solution called prefix coloring that was proposed by Le Pape, et al. in [49]. It consists in an association of meta-data to the selected IPv6 prefixes when configured by the network. Therefore, this meta-data will allow the network to describe the purpose and properties of this prefixes. This allows to the applications to make intelligent decision when selecting a prefix, especially after a handover has occured in order to maintain the session continuity, the user QoS and the perceived user quality of Experience (QoE).

- Internetwork Location Management (LM) function: its role is to manage and keep track of the internetwork location of MN in motion. The location information may be a binding of the advertised IP address/prefix, e.g., HoA or HNP, to the IP routing address of the MN, or it may be a binding of a node that can forward packets destined to the MN. It is a control-plane function and it may be deployed following the client-server protocol model. Therefore, location query and update messages may be exchanged between a Location Management client (LMc) and a Location Management server (LMs).

- Forwarding Management (FM) function: it aims at intercepting packets and forwarding them to/from the IP address/prefix assigned to the MN, based on the internetwork location information. The packets are forwarded either directly to the destination, when possible, or to some other network element that knows how to forward them to their destination. FM may optionally be split between control plane (FM-CP) and data plane (FM-DP).

Thus, from this point of view, the handover duration time is therfore given by summing the execution duration of these handover's phases. However, we can divide this duration into two main components which are: the L2 handover duration and the L3 handover duration as expressed in figure 2.11. The L2 handover takes place from the disconnection of the old network to

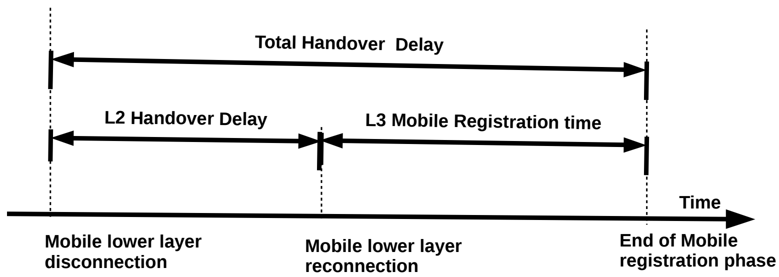


Figure 2.11 – handover main phases

the discovery of the next network. The second part takes place from when the mobile starts the registration to the new network until it has finished the configuration of its new address (also called CoA for Care of Address) and is able again to send/receive correctly the packets.

The way that all these phases are executed (sequentially or semi-parallel) and the existence of different mobility management protocols imply that there are many different types of handovers. Thus, we have proposed and established our classification in section 2.5.

2.5. Classification of the handover types

Referring to figure 2.2, the existing mobility management (i.e handover) approaches can be classified into two main classes:

- Global mobility management: in which the main mobility manager known as Home Agent (HA) is generally located in the core network (core layer of this architecture in figure 2.2) and is managed in a centralized manner. We can cite some protocol examples such MIPv4, MIPv6, NEMO, etc.

- Local mobility management: in which the mobility is managed locally at the edge of the networks (preferably in the multi service edge layer), in a small region named mobility domain and is assumed to be managed in distributed manner. Here also, we can cite the examples of PMIPv6, DMM, FDMM approaches.

Thus, we have established a classification of the main existing handover mechanisms in the table 2.2 and we provided their details and description in the subsequent rest of this section. Note that, in contrast with existing classification, the contribution of this new classification is twofold:

- Firstly, we defined our proper classification criteria (technologies and frequency switching, handover execution manner, the main handover decision actor, how many levels are involved in the handover process, etc). This allows us to give to readers a global high-level point of view of existing handovers approaches, illustrated by figure 2.12.

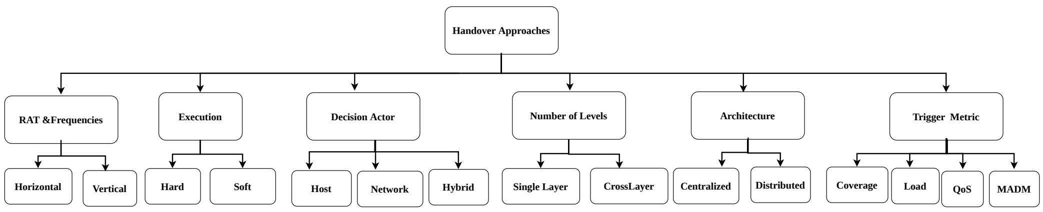


Figure 2.12 – High level point of view of existing mechanisms of handover

  By adding architecture-based and trigger-event-based classification, we have tried to make this handover's classification more exhaustive than previous works, according to our knowledge when writing this manuscript. Note also that there is no standardization available for the last category (trigger event-based handovers), which means that other parameters may be taken into account. Multiple Attribute Decision-Making (MADM)-based handovers take place when many parameters are considered in order to make the handover decision.

- Secondly, we wanted to emphasize on the distributed architecture, mainly the Distributed Mobility Management (DMM), which are newer in the litterature and still have ongoing standardization process. These DMM approaches present promising solutions and a lot of advantages compared to the traditional, centralized and bottlenecked architectures, as it is detailed in section 2.5.5.2.

Note also that these criteria are not completely exclusive, which means that a protocol can satisfy more than one criterion, as it can be seen in the description and examples' column in the table 2.2.

In the following section, details and explanation of these existing handovers'mechanisms will be given.

Table 2.2 – Main categories of handover with some examples of handover solutions

Criteria	Categories	Description	Examples
RAT&Frequency	Horizontal	Intra-system	WiFi
	Vertical	Inter-systems	WiFi to 3G [13]
Execution	Hard	Break Before Make	MIPv4 ([50]), MIPv6 ([51])
	Soft	Make Before Break	PMIPv6 ([52, 53])
Decision actor	Host-based	Mobile	MIPv4, MIPv6
	Network-based	Network	NEMO ([54]), PMIPv6
	Hybrid	Mobile-Assisted by Network or Network-Assisted by Mobile	Variables: DMM
Number of levels	Single layer	L3 or L4	NEMO, MIPv4, MIPv6, MSCTP ([55]), SIGMA
	Cross-layer	L2-L3, L2-L7	FDMM
Architecture	Centralized	Control plane and data plane	NEMO, MIPv4, MIPv6, HMIPv6 ([56])
	Distributed	Data plane or both planes	FDMM
Trigger event	Quality-based	Signal quality	RSSI-based
	Coverage-based	Coverage to a UE	Transmission range consideration
	Load balancing-based	Traffic load balance, ressource utilization	device and mobile capacity
	MADM-based	Multiple Attribute Decision-Making	Many parameters in same time

2.5.1. RAT and frequencies based classification: Horizontal and Vertical handovers

By technologies and frequency, we would like to mention the type of Radio Access Technologies (RAT) that are involved in performing the handover. Thus, horizontal handover (HHO) represents the handover that takes place using the same RAT, for example between 2 different wifi cells served by two wifi access points (AP) or a handover between two cells belonging to one of the 3GPP technologies (3G/LTE/5G). Generally, horizontal handover are triggered based on the Received Signal Strength Indicator known as RSSI.
In contrast, vertical handover (VHO) takes place when a mobile has to change the RAT technology. For example, a mobile moving from wifi to 3G or vice-versa. In order to perform vertical handover, many criteria (figure 2.10) have to be considered in addition to RSSI [13, 57, 43]. Authors of [13] have established an overview of the vertical handover techniques and estimated that 72.9% of the VHO proposals were between two RATs. They also highlight the main drawback of these proposals, which is the fact that none of these proposals provides a unique homogeneous approach that can be adapted to all the wireless technologies. In these categories, there are also inter-frequency

based handovers which occur when a mobile have to change the frequency bearer, due to interference and fading or channel quality degradation.

2.5.2. Execution-based classification: Hard and Soft handovers

In this category, we considered the moment when the handover is triggered and how resources (frequency bearer) are released from the home agent before the mobile can be attached to a new resource from the visited agent. During a hard handover, resources must be released at the home agent before that the mobile can get and attach to new available resources in the visited agent. This is the reason why this handover is often referred to as “Break before Make”. However, when a soft handover occurs, the mobile will still be simultaneously connected to both of the home and the visited agent for a while, before that the resource at the home agent might be released. This soft handover presents the benefits of avoiding many fluctuations, especially when the mobile cannot be served by the visited agent for a long time and thus, it has to be re-served by the previous home agent. This handover approach is often referred to as “Make before Break” which can also be understood as: release the previous resource if you are sure that you have been well connected to the new one.

2.5.3. Decision-actor based classification

2.5.3.1. Host-based approaches

In these approaches, the mobile (UE) is the main triggerer of the handover. The mobile takes the handover decision and informs the network about it. However, the network stills the one which takes the final decision based on radio resource’s availability in target cell. By this way, the mobile detects the beginning of the disconection, decides whether the handover is necessary or not. If the handover has to take place, the mobile will select the candidate network based on the specific parameters that are involved in the decision phase of the handover, and then, it provides all these relevant information to the network (refering to the Home Agent), which evaluates the availabilty of the resources on the targeted candidate (Visited Agent).

Some of host-based protocols and their main characteristics are:

- MIPv4 (for Mobile IPv4): it is an IPv4-based mobility protocol. Its main drawbacks are: triangular routing which always oblige the packet forwarding to pass through the HA and presents high latency and therefore, it induces packets loss. The HA also becomes a single point of failure.

- MIPv6 (for Mobile IPv6): it is an IPv6-based mobility protocol. It improves the IPv4 latency thanks to his CoA autoconfiguration. However, it suffers also from the overhead when the mobile is trying to inform about its new address to all its correspondents. MIPv6 can work in two different modes: with or without route optimization. It has to be noted that additional delay is incurred when the mobile is using the route optimization mode. In MIPv6, the HA typically provides the AF function; the LM function works on a client-server basis. LM server function is located at the HA, whereas the LM client is done at the MN; the FM function is distributed between the ends of the tunnel at the HA and the MN.

- HMIPv6: it is a hierarchical mobility management extension for Mobile IPv6. It has been designed in order to reduce the amount of signaling packets between the mobile node, its correspondent nodes, and its home agent. It consists in using a new node called the Mobility Anchor Point (MAP), which can also be used to improve the performance of Mobile IPv6 in terms of handover speed. The main advantages and improvements given by adding this MAP is primarily the following:

  - The fact that the mobile node now sends binding updates to the local MAP which should be closer, rather than the home agent (HA) (which is typically further away) and correspondent nodes (CNs), reduces the handover latency and subsquently decreases the mobile disconnection time.
  - Only one binding update message needs to be transmitted by the mobile node (MN) before traffic from the HA and all CNs is rerouted to its new location. This reduces the overall overhead from the mobile. Note also that this is independent from the number of CNs with which the MN is communicating, which can be high in a dense traffic scenario.
  - As this MAP is essentially a local home agent [56], it will allow the minimization of packet loss by reducing the latency and the reconnection time of the mobile.

  One major drawback of HMIPv6 is that it always needs the availability of this additional nodes, which means additional resources. In the HMIPv6 protocol, the Mobility Anchor Point (MAP) serves as a location information aggregator between the LM server at the HA and the LM client at the MN. The MAP also provides the FM function to enable tunneling between HA and itself, as well as tunneling between the MN and itself.

- Fast MIPv6 [58]: It is a MIPv6 extension whose aim is to optimize the handover latency, by defining new router discovery mechanism before the handover in order to reduce the new network discovery latency. As it must be known that the handover latency depends on many IP protocol operations delay such as movement detection, new Care-of Address configuration, binding update and link-switching, it is important to mention that this specification does not address the improvement of the link-switching latency. Thus, the problems that FMIPv6 mainly addresses are resumed in: how to allow a mobile node to send packets as soon as it detects a new subnet link and how to deliver packets to a mobile node as soon as its attachment is detected by the new access router [58]. Therefore, it defines which IP protocol messages are necessary for its operation regardless of which link technology is used. Subsequently, it is applicable when a mobile node has to perform IP-layer operations as a result of handover and has updated the protocol header format for the Handover Initiate (HI) and Handover Acknowledge (HAck) messages defined in its previous version in RFC 5268 [59].

- MOBIKE [60]: It is a mobility and multihoming extension to Internet Key Exchange (IKEv2). This extension allows the IP addresses associated with IKEv2 and tunnel mode IPsec Security Associations to change. MOBIKE protocol may be used by a mobile Virtual Private Network (VPN) client in order to keep the connection with the VPN gateway active while moving from one address to another.

  This extension could be used also in a scenario where a multihomed host wants to move the traffic to a different interface if, for instance, the one currently being used stops working. Note that MOBIKE is best suited for situations where the address of at least one endpoint is relatively stable and can be discovered using existing mechanisms such as DNS.

2.5.3.2. Network-based and Hybrid approaches

In network-based handover, the network makes handover decisions and handles the mobility management on behalf of the mobile. This allows to make the handover transparent to the mobile. Some network-based handover protocols, such as Network Mobility (NEMO) assume a good stability of the mobile network. Then, they assign a Home Network Prefix (HNP) to a mobile router which serves all mobiles within the mobile network in motion.

One of the most promising protocol solutions in mobility management is the PMIPv6. PMIPv6 is the only network-based standardized protocol for mobility management. It is specified in RFC 5213 [52]. PMIPv6 provides a network-based mobility management to the hosts that are connecting to a localized network domain referred to as PMIPv6 domain. PMIPv6 introduces two new functional entities which are the Local Mobility Anchor (LMA) and the Mobile Access Gateway (MAG) that are illustrated in figure 2.13. The MAG is the entity which is responsible of detecting the Mobile Node's (MN's) attachment and therefore providing IP connectivity to the MN. On the other side, The LMA is the entity which is responsible of assigning one or more Home Network Prefixes (HNPs) to the MN's network interfaces. LMA is the topological anchor for all traffic belonging to the MN.

In order to perform its topological anchor functionnalities, the LMA must maintain a database called Binding Cache (BC) in which it stores an entry for each MN located in the PMIPv6 domain. Thus, each entry represents a mapping between the MN and his MAG, with also a list of assigned HNPs to this MN.

As normal database, the LMA must perform the basic functions of persistent storage, known as CRUD (Create, Read, Update, Delete) operations, each time that a change is necessary in the BC. This process always starts by performing a lookup in the BC to verify whether a MN entry is already available in the BC or not. Depending on the number of entries in this BC, which is proportional to the number of MNs in the PMIPv6 domain, this lookup process can take a long time and may cause the handover latency to increase. Thus, a good conception of the storage structure to be used in BC is of great importance. For this purpose, in [61], authors proposed an improvement in handover performance by just adding a hash function in the BC representation. Their proposed solution is called PMIP-HD (Hash-based Distributed PMIPv6) and will be explained later in this section. In this thesis works, we also consider the use of a hash function and we designed our solution based on the PMIP-HD architecture.

To perform these CRUD functions, PMIPv6 entities exchange messages as illustrated in figure 2.13. As shown in this figure, the two main messages are denoted PBU (Proxy Binding Update) and PBA (Proxy Binding Acknowledgement).

In PMIPv6, the local mobility anchor (LMA) provides the Anchoring Function (AF), that allows the allocation of new IP address (HNPs). For the inter-network Location Management (LM) function, the LM server is also

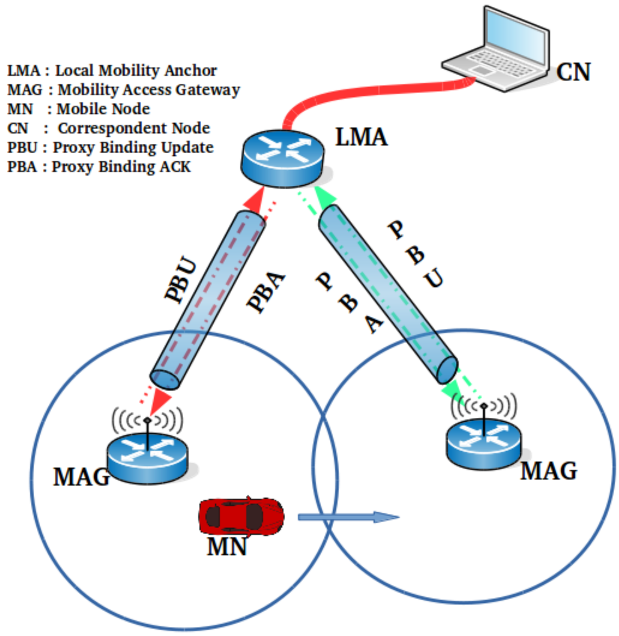


Figure 2.13 – PMIPv6 architecture [62]

located at the LMA, whereas the LM client is placed at the mobile access gateway (MAG). The Forwarding Management (FM) function, which intercepts and forwards packets from/to the MN, is distributed between the ends of the tunnel at the LMA and the MAG. As it was done by authors in [58], where they proposed a fast handover version of MIPv6, Yokota, et al. [63] have described the requirements needed in order to perform a fast handover for PMIPv6 in RFC 5949.

Note that, compared to host-based approaches, the primary features and goals of network-based handover protocols [64] are:

- Support for unmodified MNs: unlike MIPv6, a network-based approach should not require any software update for IP mobility support on MNs.
- Support for IPv4 and IPv6: although the initial design of a network-based approach uses an IPv6 host, it is intended to work also with IPv4 or dual-stack hosts as well.
- Efficient use of wireless resources: a network-based approach should avoid tunneling overhead over a wireless link. Hence, it should minimize the overhead within the radio access network. We may recall that, in PMIPv6 for example, this overhead could come from the exachange of PBUs and PBAs messages as illustrated by figure 2.13.

- Handover performance improvement: a network-based approach should minimize the required time for handover, also known as the handover latency.

That is why, in order to enhance the PMIPv6 functionalities, some PMIPv6 extensions such as the multihoming support [65] and flow mobility [53] have been proposed. It is to be noticed that we can have local multihoming or remote multihoming as described in [section 3.2.4] of [66].

In order to handle multihoming, one of the promising solution is the use of logical interface. As specified in section 3.2.4 of [66], the importance of a logical interface is that it may be bound to multiple physical interfaces, in order to increase the reliability or throughput between directly connected machines by providing alternative physical paths between them. This is achieved by performing a so called "link-layer multiplexing" which makes the protocols above the link layer unaware that multiple physical interfaces are present. However, it is specified that the link-layer device driver must be responsible for multiplexing and routing packets across the physical interfaces, without specifying how it is achieved.

For that purpose, we can distinguish two requirements issues for multihoming:

- A host **may** silently discard an incoming datagram whose destination address does not correspond to the physical interface through which it is received.

- A host **may** restrict itself to send (non-source-routed) IP datagrams only through the physical interface that corresponds to the IP source address of the datagrams.

This introduces the terms of strong ES (End System i.e host) model and weak ES model. For the Strong ES model, a host **must** silently discard an incoming datagram whose destination address does not correspond to the physical interface through which it is received. Furthermore, a host **must** restrict itself to send IP datagrams only through the physical interface mapped to the datagrams IP source address. On the other hand, the weak ES allows the host to act as gateway for some packets/datagrams. For that, a weak ES **must not** silently discard an incoming datagram for which the destination address does not correspond to the physical interface through which it is received. More, a weak ES **must not** restrict itself to send (non-source-routed) IP datagrams only through the physical interface that corresponds to the IP source address of the datagrams.

Consequently, the weak ES problem becomes that it may cause the Redirect mechanism to fail. In fact, if a datagram is sent out to a physical interface that does not correspond to the destination address, the first-hop gateway will not realize when it needs to send a Redirect. On the other hand, if the host has an embedded gateway functionality, then, it has routing information without listening to Redirects.

This is why we proposed the MIVH (Mobile Internal Vertical Handover) by describing and conceiving the use of logical interface for handover in the VANETs specific use-case. Meanwhile, some researches [67, 68, 69], have been made on the use of logical interfaces in PMIPv6 in order to enable the flow mobility. In [70], Yang et Al. have proposed an approach of using multi-link connection by adding two additional components: Multi-Link Adaptor (MLA) and Multi-Connection Manager (MCM) in the mobile node and core network respectively. However, the robustness principle:

> "Be liberal in what you accept, and conservative in what you send"

which is particularly important in the Internet layer, is also applicable in their solution and in PMIPv6 in general. This means that it stay applicable wherever one misbehaving host can deny internet service to many other hosts [66]. Their solution is still based on global and centralized architecture which can stay facing the disadvantages of centralized system such as overhead, bottleneck, single point of failure and no scalability as described in section 2.5.5.1. It might present a high handover latency due to exchanged control messages between the MLA and MCM (same case of MIPv4) depending on the distance between the mobile (UE) and the core network (MME : Mobility Management Entity or HA). In addition, when considering the use of the OCB (Outside the Context of BSS (Basic service set)) mode in VANETs [71], we do not always have/need the main functionalities of the MME, the HSS (Home Subscriber Server) and the AAA (Authentication, Authorization and Accounting) server). This is because the OCB mode allows all the mobiles in the transmission range to directly communicate with each others, neither authentication/association procedures nor security mechanisms are often supported, thus the data exchange should (and need to) be established in fractions of seconds. Thus in OCB:

- No authentication
- No Association
- No Encryption. Security properties are ensured by higher level protocols

This is used in IEEE 802.11p, which is an extension of IEEE 802.11a in order to lessen the connection process's delay and to maximize the communication period. Other IEEE 802.11 amendements and improvements have been proposed such as High Throughput (HT) with 802.11n and Very High Throughput (VHT) with 802.11ac [1].

The classical PMIPv6 architecture also suffers from this robustness issue. Therefore, many PMIP extensions have been proposed in the literature [63, 65, 53, 67, 68, 69, 70, 72] in order to improve the PMIPv6 performance. They almost consist in extending/modifying the manner that these signaling and updating control messages are exchanged or extending the content of the exchanged messages.
This is the case in [62], where there is an introduction of the Proxy Binding Query (PBQ) and Proxy Query Acknowledgement (PQA) as illustrated in figure 2.14 [62].

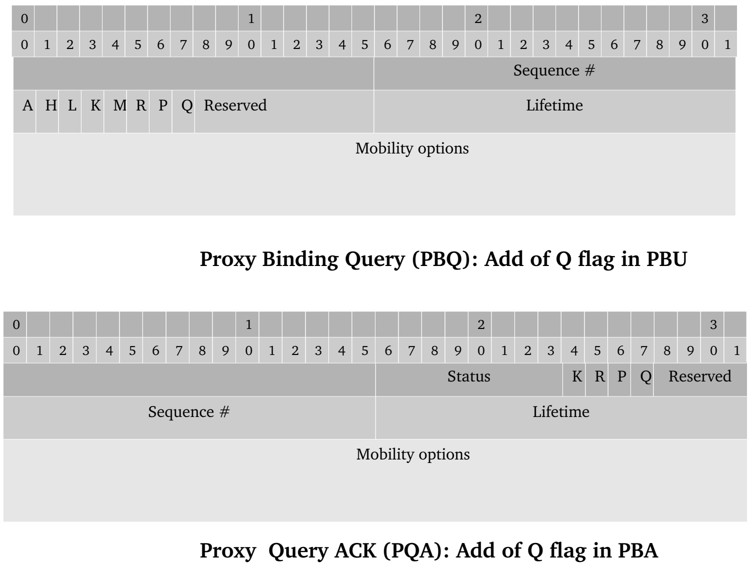


Figure 2.14 – PBU and PBA extended format to give respectively PBQ and PQA by adding the Q flags for P-DMM schemes [62]

However, these extensions are based on the centralized architecture of PMIPv6 and they are still facing the problem of centralized LMA, which becomes a bottleneck and single point of failure with critical scalability issues, depending on the number of connected MNs in the PMIPv6 domain.

[1] https://www.electronicdesign.com/communications/understanding-ieee-80211ac-vht-wireless

Furthermore, the consequent overhead created by the exchanges of updating messages can be very disastrous due to the above mentioned centralization disadvantages.

Therefore, IETF (Internet Engineering Task Force) have discussed and recently proposed PMIP-based Distributed Mobility Management (DMM) that we will explain in section 2.5.5.2.

Thus, the hybrid approaches consist in the combination of host-based and network-based ones. Depending on whether it is the mobile or the network which starts the handover process, the resulting hybrid handover approach is often called Mobile assisted by the network or Network assisted by the mobile, respectively.

2.5.4. Number of levels-based classification : single layer and cross-layer approaches

This category was created to consider how many TCP/IP layers are involved when performing the mobility management. Single layer category represents the handover approaches in which only one layer is mainly involved. While cross-layer approaches are for handovers in which an interaction between at least 2 layers has to take place in order to achieve the mobility management. Many studies have been carried out in this handovers'category. A classification and review of studies on single layer based handover found in the litterature, alongside their respective advantages and disadvantages are reported in table 2.3.

Table 2.3 – Single layer approaches overview.

Study	Advantages	Weaknesses
[73]	Can be easily implemented , proposed scheme works better for downward vertical handoff, avoids packet loss	No consideration on reputation information exchange
[74]	Provide the necessary handoff support	Requires upgrading both transport layer and application layer on both mobile hosts and internet servers. So the deployment's cost is still too high to become feasible

Continued on next page

Table 2.3 – continued from previous page

Study	Advantages	Weaknesses
[75]	Successful Handovers, Intelligent network selection	High resource consuming by receiving current network condition information and wasteful in the variable wireless environment
[76]	Focused on network and terminals	Complexity of computing
[77]	Improved the energy efficiency at the end-user mobile device, while maintaining good user perceived quality levels	Does not generate the weight of the effective NS parameters
[78]	D-PMIPv6 can improve the performance in terms of the packet delivery cost, prevent some packet-flooding attacks	Does not fit for flat architectures
[79, 80]	SCTP can quickly determine the loss of a packet; congestion control; Transportation layer fragmentation	SCTP uses a comprehensive 32 bit CRC32c checksum which is expensive in terms of CPU time
[81]	The solution is realistic and not very complex to implement in current mobile devices and networks	No consideration on user location
[82]	Maintain connections, Maximize user throughput	No consideration on details of the network integration as well as the handoff management
[83]	optimal network selection	No support of same level of quality to the packet flow during and after the handoff
[84]	Performance improvement	Lack of consideration on setting up the information server , Non management on the MIIS

We have also summarized in table 2.4, the cross-layer based handovers found in the literature by extending related works of previous study done by [44] on this handover's category.

Table 2.4 – Cross-layer based handover literature overview.

Study	Advantages	Weaknesses
[85]	Successful handovers, reduces the signaling overhead, minimizes packet loss.	Handover execution phase only on the Mobile IPv6, protocol is not open for any wireless network
[86]	Use of link layer information gives better performance in term of handoff latency and packet loss	No consideration on switching cost
[87]	context-awareness, multiple application, SLA and acceptance metrics, removing access router discovery, reduce information access time, HVN emulator	scalability, no strong consideration of lower layers (L1-L3)
[88]	Provide no dropping probability, avoid unnecessary handoff, different networks parameters	No dwell time to check the condition of the RSS comparison
[89]	Reduced handover failure, reduced ping-pong effect, reduced handover delay	Increased packet loss, increased signaling, unsuitable for real time applications
[90]	Increased QoS	High packet loss
[91]	Successful handovers, better network selection, lower handover processing delay	High latency, slow training and learning
[92]	Reduced handover delay, reduced packet loss, intelligent network selection, user satisfaction for QoS	Increased complexity, higher decision processing delays
[93]	Much lower computational cost, optimization functions for applications (voice, video and web)	Not examine handover triggering, high ping-pong effect, lack of efficient network scanning mechanism.
[94]	Supports better (ABS), provides context-aware handover.	Need to be more fault-tolerant when experiencing it
[95]	Low signaling cost, guaranteed QoS	Lack of ubiquitous access of data, lack of QoS mapping procedure
[96]	Reduce handover latency, reduce ping-pong effect	Computational problems

Continued on next page

Table 2.4 – continued from previous page

Study	Advantages	Weaknesses
[97]	Low handover blocking rate, high throughput, optimized handover decision delay	Excessive load, high handover latency, difficult to estimate cost
[98]	Low handover blocking rate, reduced ping-pong effect, ranked network selection, reduced processing delay.	High latency, degraded QoS, minimum number of parameters is considered
[99]	MN can be better informed of the decision, reduced the amount of handovers.	Additional decision parameters are required
[100]	Satisfied load balancing criteria without overloading	No consideration on other parameters in utility functions
[101]	Low complexity.	No consideration on the user location
[102]	Adaptive to a wide range of conditions	Complexity
[88]	SWGoS has competitive utilization, adaptive approach.	Complexities of the algorithms, non dropping probability
[103]	Improvement over SAW and GRA.	Implementation complexity
[104]	Avoid unnecessary handoffs	No consideration on switching cost from the aspect of users.
[105]	Improved performance of the FMT in a real environment, reduced packet losses, limited the redundant traffic	Implementation complexity
[94]	Efficient resource management, improved efficiency	Additional decision parameters are required to ensure better QoS
[106]	High adaptation, throughput improvements	High handover delays
[58]	Reduced latency, decreased number of signaling.	Increased tunneling overhead.
[107]	Have low signaling cost	Handover latency and failure
[108]	Sustained cooperation between users and networks	No consideration on network reputation building

These single layer and cross-layer summaries are given for guideline purposes, interested readers and researchers are encouraged to read the respective articles in order to get more details on the aforementioned solutions, advantages and disadvantages alongside performance metrics that were used in order to validate each proposition.

2.5.5. Architecture-based classification: Centralized vs Distributed architectures

2.5.5.1. Centralized architectures

Most of existing network-layer's mobility management protocols are primarily based on a mobility anchor to ensure connectivity of a mobile node by forwarding packets destined to, or sent from, the mobile node after the node has moved to a different network [47]. Therefore, this mobility anchor is centrally deployed in the sense that the traffic of millions of mobile nodes in an operator network is typically managed by the same anchor. The advantages of these centralized approaches reside in its simplicity and the capabilities of the central anchor to follow user movements by simply rerouting the packets over tunnels created with the current access router of the mobile (MN). However, in these approaches, the mobility anchor (HA) represents a single point of failure and induces scalability issues (cardinal point for the control and data plane for millions of users), which also leads to suboptimal paths between MNs and their communication peers [109].

As stated in [110], centralized mobility solutions are prone to several problems and limitations: longer (sub-optimal) routing paths, scalability problems, signaling overhead (and most likely a longer associated handover latency), more complex network deployment, higher vulnerability due to the existence of a potential single point of failure, and lack of granularity on the mobility management service (i.e., mobility is offered on a per-node basis, not being possible to define finer granularity policies, as for example per-application). These problems leads to the specification of distributed mobility management protocols in order to lessen these handover and network performance issues.

2.5.5.2. Distributed architectures

The current mobile network are often centralized-based. This is notably the case of LTE in which every packet from external networks have to be routed through the Serving Gateway (S-GW) and Packet Data Network (PDN) Gateway (P-GW) which aggregates different packets from different mobility flows. Those centralized models suffer from some scalability issues due to the traffic and signaling handling. However, the deployment of extremely dense radio networks addresses the need to expand the network capacity, offering an increased bandwidth per user per unit of area [109]. This is why Distributed Mobility Management (DMM) is very essential in order to provide a more flatter mobile network which might permit traffic to be routed without traversing core links unless necessary. This is supposed to be the case in 5G in order to support the IoT adressing needs. The main concept behind DMM solutions is bringing the mobility anchor closer to the MN.

The distributed mobility management presents a lot of advantages and has promising solutions while avoiding the centralized approaches problems. Some of its advantages are:

- providing efficient mobility management
- ensuring scalability, optimal routing while avoiding single point of failure issue.
- taking advantages from cross-layer (for example by using MIH (Handover L2) and PMIPv6 (Handover L3)).
  Note that there have been some improvements and extensions of PMIPv6 from which PMIPv6-based DMM should benefit from. Among them, there are :
  - The use of a runtime Local Mobility Anchor (LMA) assignment support for PMIPv6 which is defined and explained in [111],
  - specification on how to use a localized routing for Proxy Mobile IPv6, which is standardized in [112], and
  - the use of a dynamic LMA solutions that are available in [113].

Requirements of DMM are specified in RFC 7333 [110]. A good comparison between centralized and distributed approaches is also detailed in this RFC 7333. DMM practices and gap analysis are detailed in RFC 7429 [47]. [47] analyzed how existing IP mobility protocols have been deployed in distributed mobility management, in order to identify their limitations when compared to the requirements for an efficient distributed mobility management solution as described by the standards.

The main objective of their work was to analyze and take advantage from important mobility management functions that have been already performed many years before and which have been developed and deployed in centralized mobility management approaches. Therefore, they tend to extend these functions in order to provide distributed mobility management.

Recently, some DMM-based solutions have been proposed and can be classified into two groups of approaches [114, 115] as illustred in figure 2.15:

- Partial DMM (PDMM): in which the control plane remains centralized while the user data plane has been distributed.

- Fully DMM (FDMM): in which both of the control plane and the user data plane are distributed and are executed at the edge of the network. Edge network paradigm is currently most referred in Edge computing [116, 117] or in Multiple Edge Computing (MEC) [118].

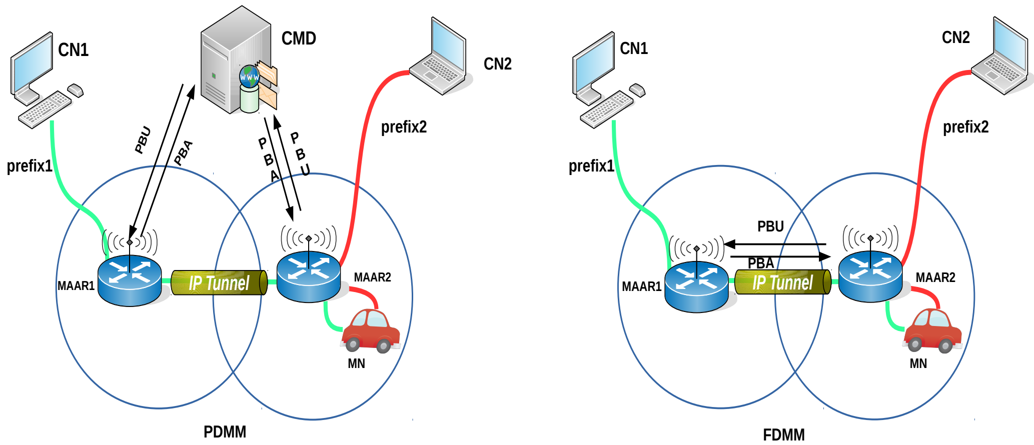


Figure 2.15 – General architecture of Partial DMM and Fully DMM approaches

In [119], authors have made a comparison between the performances of different network-based solutions. They have carried out an analytical evaluation on network-based IPv6 Distributed Mobility Management Solution. They have considered the scalability and reliability problems of hierarchical and centralized mobility approaches. They primarily took into account the signaling overhead, the data packet delivery cost and the handover latency. Then, they compared their results to those of the standardized network-based and centralized mobility protocol: Proxy Mobile IPv6. In order to validate their analysis, they made a proof of concept of their design using an experimental setup with an implementation of the DMM solution and a performance assessment on handover latency was made in [119].

Many works of standardization of DMM have been carried out, but at the time of writing this chapter, there are still some works in progress as it can be seen in the Proxy Mobile IPv6 extensions for DMM draft [120].

Regarding the implementation methods of DMMs, we can classify the DMM implementation solutions into 3 main categories [109] as following:

- PMIPv6-based: these solutions consist in the modifications of the classical IP mobility protocols, in particular the well known and standardized PMIPv6.

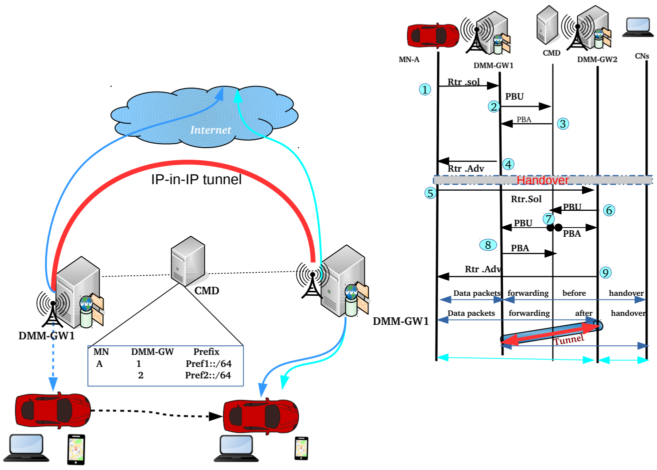


Figure 2.16 – Architecture and flow chart of PMIPv6-based DMM implementation [109]

As it can be seen on the left side of figure 2.16, in this solution implementation, the MAG is replaced by another advanced entity called the DMM gateway. This entity (DMM-GW) evolves from a classical PMIPv6's MAG and is now provided with links to the Internet. This allows the DMM gateway to forward packet without implying paths traversing the LMA. Hence, the DMM-GW acts as a plain access router (i.e., no tunneling) to forward packets to and from the Internet. Moreover, the PMIPv6's LMA is reduced to an only control plane entity, referred to as the control mobility database (CMD), which stores, for every MN, all the prefixes advertised to the MN, respectively mapped to the identifier of the DMM-GW that advertised them, and to which DMM-GW the MN is currently connected. The control plane (router sollicitation, PBU, PBA messages exchange) and data forwarding operations are illustrated by the right side of figure 2.16 and are very similar to those of PMIPv6.

- SDN-based: this second category of DMM solutions focuses on SDN paradigm which stands for Software Defined Networks. In the SDN concept, the network administrators have the possibilities to remotely control and program the behavior of both the traffic and the whole network in a centralized way, without requiring independent access and configuration to each hardware device, also referred to as endpoint devices of the network. With SDN, control plane (which is responsible of signaling and location management) and data plane (responsible for packet forwarding) are completely decoupled, in contrast of traditional networks. This decoupling and the programmability of SDN make easy the networking and deployment of new protocols and new applications, which makes them very flexible and efficient.

All those advantages are made available thanks to a network entity called Network Controller (NC) on which control plane tasks are executed, using some common application programming interface (API) such as the well known OpenFlow [121, 122].

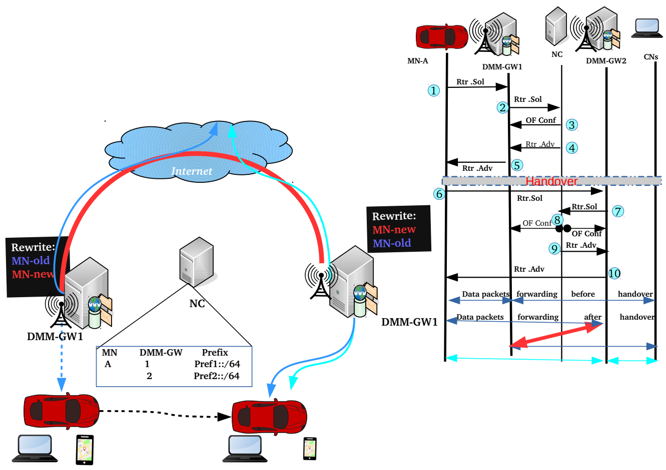


Figure 2.17 – Architecture and flow chart of SDN-based DMM implementation [109]

The SDN-DMM solution architecture, represented by figure 2.17, is like PMIPv6-DMM solution in which the CMD is now replaced by the network controller (NC). The sequence flow is almost the same, except that after the detection of MN attachment to a DMM-GW, the NC is informed and has to configure the openflow rules in each DMM-GW visited by the MN, as shown in step 3 and step 8 on the flow chart on the right side of figure 2.17. Mobility is therefore achieved by combining translation and forwarding openflow rules on DMM-GWs, which means that upon the reception of an anchored flow packet, each DMM-GW has to rewrite the destination address and put the new MN's location address (MN-new) before forwarding this packet. Authors also mentionned that there is no need to use tunnels in this SDN-based DMM solution.

- Routing-based: this category regroups all the DMM solutions which mainly leverage the traditional existing IP routing protocols such as Border Gateway Protocol (BGP) and DNS in order to suppress the central anchor (CMD in PMIPv6-based and CN in SDN-based) as shown by figure 2.18. This makes this solution fully distributed unlike the two previous DMM ones which were partially distributed.

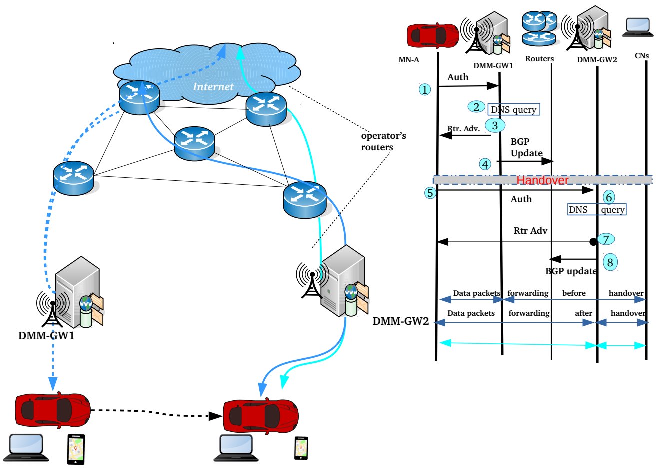


Figure 2.18 – Architecture and flow chart of Routing-based DMM implementation [109]

The main characteristics of each one of these 3 DMM approaches alongside a testbed-based validation and performance assessments have been thoroughly described in [109] and are summarized in the table 2.5.

We would also emphasize the fact that the required time for layer 2 switch, the layer 3 handover and ping traffic recovery was also measured for each implementation type.

In [62], authors have proposed many DMM candidates schemes such as Signal-driven PMIP (S-PMIP), Data-Driven Distributed PMIP (DD-PMIP) and Signal-Driven Distributed PMIP (SD-PMIP). However, these schemes are not efficient for real-time and critical applications, especially for self-driving cars in VANETs.

Table 2.5 – Comparison of DMM solutions based on the implementation and performance analysis in [109]

Type / perf. criteria	PMIPv6-based DMM	SDN-based DMM	Routing-based DMM
group of DMM & Main component	Partially distributed Central mobility database	Partially distributed SDN controller	Fully distributed
MN's Multiple IP	Mandatory	Mandatory	supported
Mobility anchors & Depends on	Multiple IP flows generation	Multiple IP flow generation	None
Tunneling:IPv6 in IPv6	Yes	No	No
Route optimization	No support for anchored IP flows	No support for anchored IP flows	Yes for all IP flows
Handover latency	Low	Low	High
Signalling Overhead	Low	Low	High
Depends on number of	Active anchors	Active anchors	Routers

In [61], authors proposed a Distributed PMIPv6 based on a hash function[2](PMIPv6-HD), which presents performance improvement in terms of data packet delivery cost after a handover.

2.5.6. Triggering event-based classification

This categories mainly focuses on the parameters that are continuously monitored in order to initiate the handover process. In other words, the parameters taken into account during the handover decision phase. We distinguish :

- Quality-based: For many applications, especially safety applications, there is a minimun acceptable quality level that must be maintained in order to achieve a continuous session connetivity. When a moving mobile (UE) detects a better signal quality (referenced in form of RSSI, RSRP or RSRQ) from a neighbouring cell, it can trigger a handover to this cell even if the serving node signal quality was still above an acceptable threshold. In this case, this handover is called quality-based handover. The problem of this method is that it could lead to ping-pong effect.

- Coverage-based: this handover occurs when the serving node is no more able to provide coverage to UE, which makes the handover iminent in order to ensure an uninterrupted service.

[2] https://interactivepython.org/runestone/static/pythonds/SortSearch/Hashing.html

- Load-balancing: In order to improve the networks' resources utilization, a network-based handover can be triggered in order to balance the traffic load accross different cells and possibily accross different EnodeBs.

- MADM: This category refers to the multi-attributes decision methods which consider multiple parameters in order to make a final decision on the necessity of handover. Note that there is no standardization proposed in this category, which means that the list of parameters can be long. Therefore, we used the MADM terms in order to represent all the possible combinations of multiple parameters that can be taken into account in the handover decision process. A survey of existing MADM-based handover proposals can be found in [123].

2.6. Conclusion

In this chapter, we have given the general information and background about the VANETs and IoV domain. Then after, we have provided background information about the handover, starting by the basic handover operations, then the vertical handover phases, and after that we have proposed our proper classification of the handover mechanisms found in the litterature.

Therefore, looking for efficient solutions which might help in establishing a continuous connectivity for VANETs and autonomous vehicles deployment, we have noticed that taking advantages of cellular networks (their coverage and availability around the world) in combination with the vehicular networks is a good alternative to the RSU expensive deployment. Thus, we wanted to benefit from the presence of cellular networks and make handover between vehicular networks and cellular networks. Consequently, we have therefore continued our journey by studying the LTE technology in order to see how we can propose efficient algorithms of vertical handover in VANETs.

Furthermore, given the VANETs characteristics and V2X services requirements, we found that efficient handovers algorithms might be based on multiple parameters, collected from different TCP/IP layers. Thus, we found the MADM methods to be a good candidate for selection methods, when dealing with handover issue in HVN.

Thus, in the following chapter 3, we are going to see the study that we carried out about the handover protocols and the MADM algorithms, that can be used in heterogeneous networks that include LTE. Thereafter, we will propose our vertical handover mechanisms which are adapted to the VANETs field.

Chapter 3

Study of handover algorithms and handover protocols in heterogeneous networks with LTE

Unlike the general wireless networks (WLAN, WAVE), seamless handover in cellular networks, especially the LTE systems, involves many processes and many communications between the network components.

In LTE [124], the hybrid handover approach is often used. In fact, the User Equipment (UE) first sends measurement reports information to the network. Then, based on those measurements, the eNB of E-UTRAN network asks to the UE to move to a selected target cell or target network. As you can see, both the mobile (vehicle) and the network are involved in the LTE handover process, which leads to the network assisted by the mobile handover approaches.

Figure 3.1 shows a case of internetworking between the LTE technology (through its E-UTRAN radio access), 2G (GERAN) and 3G (UTRAN) radio access technologies.

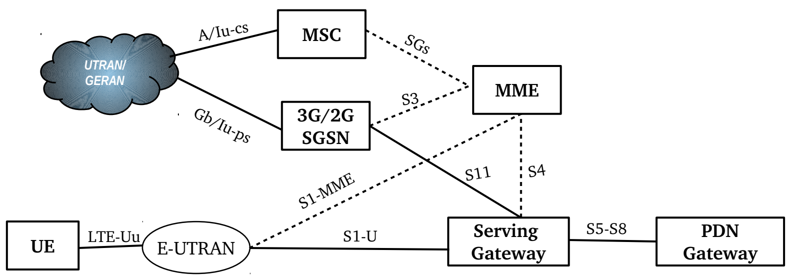


Figure 3.1 – General architecture of LTE heterogeneous networks [125]

It also illustrates the main components of the LTE systems (such as the E-UTRAN, the MME, the Serving Gateway and the PDN Gateway) that are often involved in the LTE handover process. Details of these components will be given in the following section. In LTE, the control functions that were implemented in Radio Network Controller (RNC) for 3G and in Base Station Controller (BSC) in 2G have been transfered in the eNodeB. Then, the functionnalities of the Mobile Switching Center (MSC server for voice commutation) and SGSN (for data forwarding) have also been transferred in the E-UTRAN in order to be executed closely to the mobile. This fact has contributed in the improvement of the LTE network performances in terms of datarate, bandwidth and latency's reduction, compared to its predecessors (2G,3G). Then, both the E-UTRAN and SGSN are connected to a Mobility Management Entity (MME) and a Serving Gateway (S-GW), generally through an optical fiber network called mobile backhaul.

Thus, in this chapter, we have started by studying the main components of the LTE system in order to deduce their main roles in the handover process, before using them in the study of handover protocols (such as MIH, ANDSF, PMIPv6) and handover algorithms that are applied and used in the LTE standards.

3.1. LTE handover overview

The general LTE handover architecture can be seen as illustrated by figure 3.2

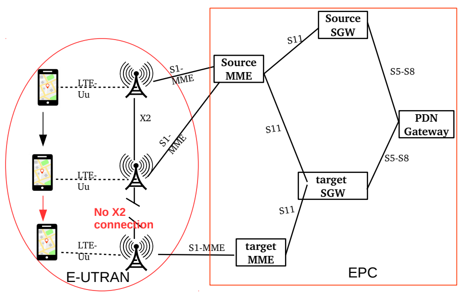


Figure 3.2 – LTE S1-based handover architecture

These main components, that are always involved in the LTE handover, are as following, as described and standardized in [124]:

- E-UTRAN: it stands for Evolved Universal Terrestrial Radio Access Network. It is mainly composed by the eNodeBs. It is primarily described in TS 36.300 and then in TS 23.401 [124]. Its main functions are :

- Header compression and user plane ciphering
- MME selection, if not provided in UE information
- Uplink bearer level rate enforcement via means of uplink scheduling (limiting the amount of UL resources granted per UE over time)
- DL bearer level rate enforcement based on UE- Aggregate Maximum Bit Rate (UE- AMBR)
- UL and DL bearer level admission control
- Explicit Congestion Notification (ECN)-based congestion control [126, 127, 128, 129]

* Mobility Management Entity (MME): it is responsible of:
  - Non-Access Stratum (NAS) signaling and security signaling
  - Inter CN node signaling for mobility between 3GPP access networks (terminating S3)
  - UE reachability in EPS Connection Management (ECM)-IDLE state (control and execution of paging retransmission)
  - Tracking area list
  - Mapping from UE location to time zone, and signaling a UE time zone change associated with mobility
  - Selection of PDN GW (P-GW) and Serving gateway (S-GW)
  - Selection of target MME during handover where there is need to change MME
  - Selection of SGSN for inter-RAT handovers to 2G or 3G 3GPP access networks.
  - Roaming through S6a interface towards Home Subscriber Server (HSS)
  - Authentication, authorization
  - Bearer management functions such as dedicated bearer establishment
  - UE reachability procedures, support of relaying function

- The S-GW: it acts as the mobility anchor for inter-networking with other 3GPP technologies such as GSM and UMTS. This is the gateway which terminates the interface towards E-UTRAN. It is connected to the PGW through S5/S8 on which PMIPv6-based or GTP-based handover can be executed. Some of its main functions are:
  - Providing a mobility anchoring for inter-3GPP mobility such as terminating S4 and relaying the traffic that passes between 2G/3G system and PDN GW;
  - Serving as the local mobility anchor point for inter-eNodeB handover, which often takes place through X2 interface when available.
  - Packet routing and forwarding
  - Accounting for inter-operator charging. The SGW generates accounting per UE and bearer when GTP-based S5/S8 handover occurs.
  - Sending of one or more "end marker" to the source eNodeB, source SGSN or source RNC immediately after the path-switching during inter-eNodeB and inter-RAT handover. This is very important especially for assisting the reordering function in eNodeB.
- The P-GW: it serves as an anchor allowing seamless mobility to non-3GPP networks such as CDMA2000 or WiMAX.

  It is the gateway which terminates the SGi interface towards the PDN. PGW may support GTP-based and PMIP-based S5/S8 interfaces. Its main functions are :
  - UE IP address allocation,
  - DHCPv4 (server and client) and DHCPv6 (client and server) functions,
  - UL and DL service level charging and service level gating control
  - UL and DL service level rate enforcement
  - Per-user based packet filtering
  - Lawful interception
  - Transport level packet marking in the uplink and downlink, such as setting the DiffServ Code Point based on the QCI of the associated EPS bearer;
  - Accounting for inter-operator charging;

When used with GTP, PGW also performs the neighbor discovery for IPv6 functions [130, 131] and the accountig per UE and per bearer. It also supports the UL bearer binding verification and UL and DL bearer binding.

- Interfaces: they are facilities through which the communication among the aforementionned components involved in handover management takes place. The table 3.1 represents a summary of these interfaces. For more details on these interfaces roles and functions, readers are encouraged to refer to TS 123.402 (section 4.4) [132] and [124].

Table 3.1 – LTE communications interfaces

Name	**Entity A**	**Entity B**	**Functions**	**supported protocols and examples**
S1-MME	E-UTRAN	MME	Control	used in S1AP [133]
S1-C	E-UTRAN	MME	Control	used in S1AP
S1-U [1]	eNodeB	SGW	user PDU delivery, SAE bearer, inter eNodeB Path switchwing in handover	UDP/IP, GTP-U,
X2 (U-C)[2]	eNodeB	eNodeB	Control plane and User plane as in S1	
S3	SGSN	MME	Enables user and bearer information exchange for inter 3GPP access, Network mobility in idle and/or active state	
S4	SGSN	SAE S-GW	control & Mobility support	GTP
S5	SGW	PGW	Tunneling in the same PLMN	GTP, PMIP, DSMIPv6
S6a	MME	HSS	AAA	
S7	PCRF	PCEF	QoS transfer	
S8a	SGW in VPLMN	PGW in HPLMN	Tunneling between different PLMN	
S9	H-PCRF	V-PCRF	QoS policy and charging rules	
S10	MME	MME	Relocation &information transfer	
S11	MME	SGW	Reference point	
S12	UTRAN (nodeB)	SGW	Direct tunneling	GTP-U
S13	MME	EIR	UE identity check	
SGi	PGW	PDN	intra operator PDN, operator external public, private PDN [3],	
Rxi	AF	PCRF	Reference point	

Thus, the first step in LTE handover consists of measurements request/report from the mobile to the E-UTRAN through LTE-uu interfaces.

As illustrated in figure 3.3, the UE reports measurement information in accordance with the measurement configuration as provided by E-UTRAN.

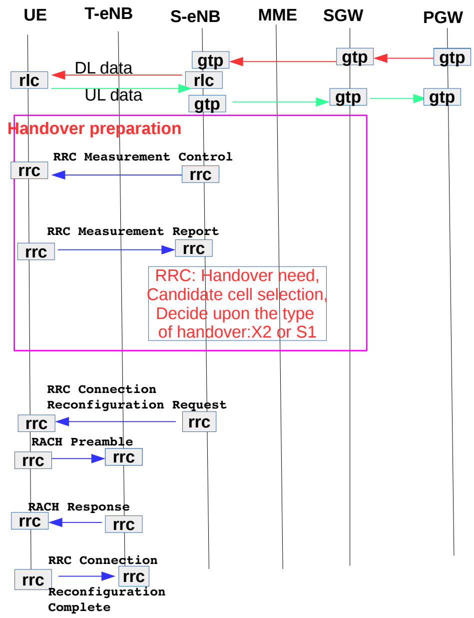


Figure 3.3 – Sequence diagram of LTE handover preparation phase

For each UE in RRC_CONNECTED state, the E-UTRAN provides a respective applicable measurement configuration by means of dedicated signaling, i.e. using the RRCConnectionReconfiguration [4] message sent to UE by E-UTRAN (i.e. source EnodeB RRC) in handover initiation phase. As specified in section 5 of ETSI TS 136.331 [134], this measurement configuration includes the following parameters:

- Measurements objects: they are objects on which UE shall perform measurements (a single E-UTRA carrier frequency in case of intra and/or inter-frequency measurements, a set of cells on a single UTRA carrier frequency in case of inter-RAT UTRA measurement, a set of cells on a single (HRPD or 1xRTT) carrier frequency in case of inter-RAT (CDMA2000).

- A list of Reporting configurations: each reporting configuration consists of reporting criterion that triggers the UE to send the measurement

[4] http://www.eventhelix.com/lte/handover/s1/#.WzO_lR2WZBQ

report in a periodical or event-driven manner and a reporting format (quantities that the UE includes in the measurement report)

- Measurement identities: reference number in the measurement report (like key in databases design).
- Quantity configuration: one quantity configuration per RAT type [135]
- Measurement gaps: periods used by the UE to perform measurements. In this periods, no transmissions (UL or DL) are scheduled

3 types of cells can be found in the measurement procedures: serving cell, listed cells in the measuremnt report and detected cells (but not listed in the measurement report). It has to be noticed that 3 main types of measurements can be performed by the UE, which are:

- Intra-frequency measurements, which occur on the downlink carrier frequency of the serving cell
- Inter-frequency measurements at frequencies that differ from the downlink carrier frequency of the serving cell
- Inter-RAT measurements of :
  - UTRAN (Universal Terrestrial Radio Access Network) frequencies
  - GERAN (GSM Edge Radio Access Network) frequencies
  - Code Division Multiple Access (CDMA2000 HRPD or CDMA 1xRTT) frequencies

The requirements of each of them are specified in ETSI 136.133 [136] and physical layer measurements values that are reported to higher layers are given in section 5 of ETSI 136.214 [135].

These measurements are related to the parameters that have to be taken into account during the handover decision phase (section 2.4) in order to decide whether a handover is needed or not and which candidate network is selected. These measurements are mainly trigerred by some specific events called triggering events. These events are conditions that are signaled by eNB to UE in the form of parameters such as thresholds, offset, and hysteresis when the event entering condition is satisfied.

5 events (A1, A2, A3, A4, A5) are standardized for intra-system handover (especially in the horizontal handover or intra-LTE handover: Automatic trigerred handover in LTE) and 2 events (B1, B2) for inter-RAT system handover. The criteria of triggering and subsequently cancelling each event

are evaluated after a layer-3 filtering has been applied [134]. This layer 3 filtering is performed following the formula below :

$$F_n = (1 - a) \times F_{n-1} + a \times M_n \quad (3.1)$$

where :
M_n is the latest received measurement result from the physical layer;
F_n is the updated filtered measurement result, which is used for evaluation of reporting criteria or for measurement reporting;
F_{n-1} is the old filtered measurement result, where F_0 is set to M_1 when the first measurement result from the physical layer is received; and

$$a = 1/2^{(k/4)} \quad (3.2)$$

where k is the *filterCoefficent* for the corresponding measurement quantity received by the *quantityConfig*;

These reporting events are summarized in the table 3.2 (Ilustration[5]):

Table 3.2 – Event report triggering in LTE [134]

Event name	**Event description**	**Parameters**	**Entering condition**	**Leaving condition**
A1	Serving becomes better than threshold	RSRP,RSRQ Threshold	$Ms - Hys > Thresh$	$Ms + Hys < Thresh$
A2	Serving becomes worse than threshold	RSRP,RSRQ Threshold	$Ms + Hys < Thresh$	$Ms - Hys > Thresh$
A3	Neighbour becomes offset better than serving	offset	$Mn + Ofn + Ocn - Hys > Ms + Ofs + Ocs + Off$	$Mn + Ofn + Ocn + Hys < Ms + Ofs + Ocs + Off$
A4	Neighbour becomes better than threshold	RSRP, RSRQ Threshold	$Mn + Ofn + Ocn - Hys > Thresh$	$Mn + Ofn + Ocn + Hys < Thresh$
A5	Serving becomes worse than threshold1 and neighbour becomes better than threshold2	RSRP, RSRQ Threshold	1)$Ms + Hys < Thresh1$ 2)$Mn + Ofn + Ocn - Hys > Thresh2$	1)$Ms - Hys > Thresh1$ 2)$Mn + Ofn + Ocn + Hys < Thresh2$
B1	Inter RAT neighbour becomes better than threshold	RSRP,RSRQ Threshold, UTRA RSCP, UTRA EcNO, GERAN, CDMA2000	$Mn + Ofn - Hys > Thresh$	$Mn + Ofn + Hys < Thresh$
B2	Serving becomes worse than threshold1 and inter RAT neighbour becomes better than threshold2	UTRA RSCP, UTRA EcNO, GERAN, CDMA2000	1)$Ms + Hys < Thresh1$ 2)$Mn + Ofn - Hys > Thresh2$	1)$Ms - Hys > Thresh1$ 2)$Mn + Ofn + Hys < Thresh2$

where:
Ms is the measurement result of the serving cell, not taking into account any

[5]http://niviuk.free.fr/lte_event.php,http://www.rfwireless-world.com/Terminology/LTE-UE-Event-Measurement-Reporting.html

offsets.
Hys is the hysteresis parameter for the respective event (i.e. hysteresis as defined within reportConfigEUTRA for the event).
Ofs is the frequency specific offset of the serving frequency (i.e. offsetFreq as defined within measObjectEUTRA corresponding to the serving frequency).
Ocs is the cell specific offset of the serving cell (i.e. cellIndividualOffset as defined within measObjectEUTRA corresponding to the serving frequency), and is set to zero if not configured for the serving cell.
Mn is the measurement result of the neighbouring cell, not taking into account any offsets.
Ofn is the frequency specific offset of the neighbour cell (i.e. offsetFreq as defined within measObjectEUTRA corresponding to the frequency of the neighbour cell).
Ocn is the cell specific offset of the neighbour cell (i.e. cellIndividualOffset as defined within measObjectEUTRA corresponding to the frequency of the neighbour cell), and set to zero if not configured for the neighbour cell.

Off is the offset parameter for the respective event (i.e. Offset as defined within reportConfigEUTRA for this event).
Mn, Ms are expressed in *dBm* in case of Reference Signal Received Power (*RSRP*), or in *dB* in case of Reference Signal Received quality (*RSRQ*).
Ofn, Ocn, Ofs, Ocs, Hys, Off are expressed in *dB*.

Note that the LTE RSRP or RSRQ can be calculated based on the following formula [6]:

$$RSRP = RSSI - 10Log(12 * N) \tag{3.3}$$

$$RSRQ = N * (RSRP/RSSI) \quad or \tag{3.4}$$

$$RSRQ = 10Log(N) + RSRP(dBm) - RSSI(dbm) \tag{3.5}$$

where :
N= Number of Resource Blocks (RB) per channel bandwidth (i.e. 6 for 1.4MHz, 15 for 3MHz, 25 for 5MHz, 50 for 10MHz, 75 for 15 MHz, 100 for 20 MHz)
RSRP : Average Received Power of a single Resource Element (RE).

[6] http://www.rfwireless-world.com/calculators/LTE-RSRP-and-RSRQ-calculator.html

RSSI: Power measured over entire bandwidth of occupied RBs.
RSRQ : is the equivalent CPICH Ec/No in UMTS.

Definitions and applicabilities states of those terms and other more references terms for UE measurements abilities are detailed in [135]

To summarize, as described in [135], the E-UTRAN transmits a *RrcConnectionReconfigurationMessage* to the UE including a measurement ID, the type, a specific command (e.g. setup, modify, release), the measurement objects, the measurement quantity, the reporting quantities and the reporting criteria (periodical/event-triggered) in order to initiate a specific measurement.

When the reporting criteria are fulfilled, the UE shall answer with a *MeasurementReportMessage* to the E-UTRAN including the measurement ID and the results.

Therefore, we distinguish three main types of handovers [137][7], as reported in the figure 3.4:

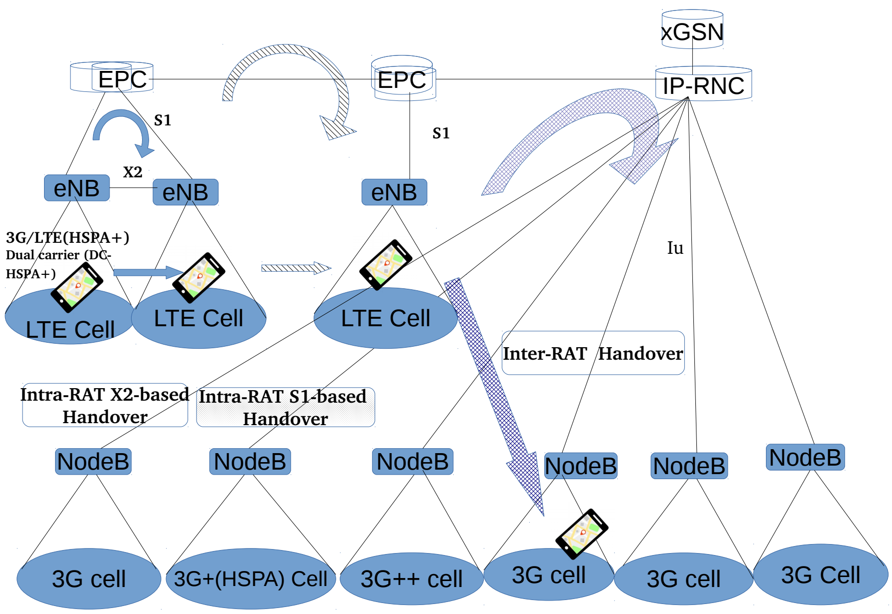


Figure 3.4 – LTE handover overview

[7] http://go.ccpu.com/rs/CCPU/images/wp-interoperability-lte.pd
http://www.3glteinfo.com/lte-handover-overview/
https://www.quora.com/What-is-the-procedure-for-inter-RAT-and-intra-RAT-handover-in-LTE

- Intra-LTE handover that happens within the current LTE network (intra-MME and Intra-SGW). In this case, the source and the target cells are both part of the same LTE network. 2 modes are also possible in intra-LTE handover :

  - with X2AP signaling [ETSI TS 123 401 v11.4.0(2013-01)]. X2 is the interface between two eNodeBs: serving eNodeB and target eNodeB in this case. When X2 interface is present, then, handover is completed without EPC (Evolved Packet Core) involvement. The release of the resources at source eNodeB is triggered by target eNodeB.
  - S1AP signaling : when X2 interface is not available and the source eNodeB and the target eNodeB are part of a same MME/SGW, then, the handover is carried out through S1 interface as illustrated in the figure 3.5

    The S-eNB initiates the handover by sending a handover required message over the S1-MME reference point. The EPC does not change the decisions taken by the S-eNB.

- Inter-LTE handover which happens from one LTE network to another LTE network (inter-MME and Inter-SGW). We distinguish :

  - Inter-MME handover which occurs when UE moves between two different MMEs but still connected to same SGW. This 2 MME that are involved in this handover are: source MME and target MME. The source MME (S-MME) is in charge of the source eNodeB and target MME (T-MME) is in charge of target eNodeB.
  - Inter-MME/SGW handover in which the UE is moving from one MME/SGW to another MME/SGW. The source eNodeB is part of one MME/SGW and the target eNodeB is in another MME/SGW. The difference with inter-MME handover is that now, two SGWs are also involved in addition to the two MMEs.

- Inter-RAT handover (or Vertical handover) which takes place between different radio technology networks, for example GSM/UMTS and LTE [138]. For a handover between E-UTRAN to UTRAN, the source eNodeB is connected to the source MME and SGW and the target RNC is connected to the target SGSN and target SGW. First of all, the required resources have to be reserved in UTRAN system and then the handover may be carried out. Similarly to the IEEE 802.21 MIH standards, 3GPP group has standardized a mechanism called Access

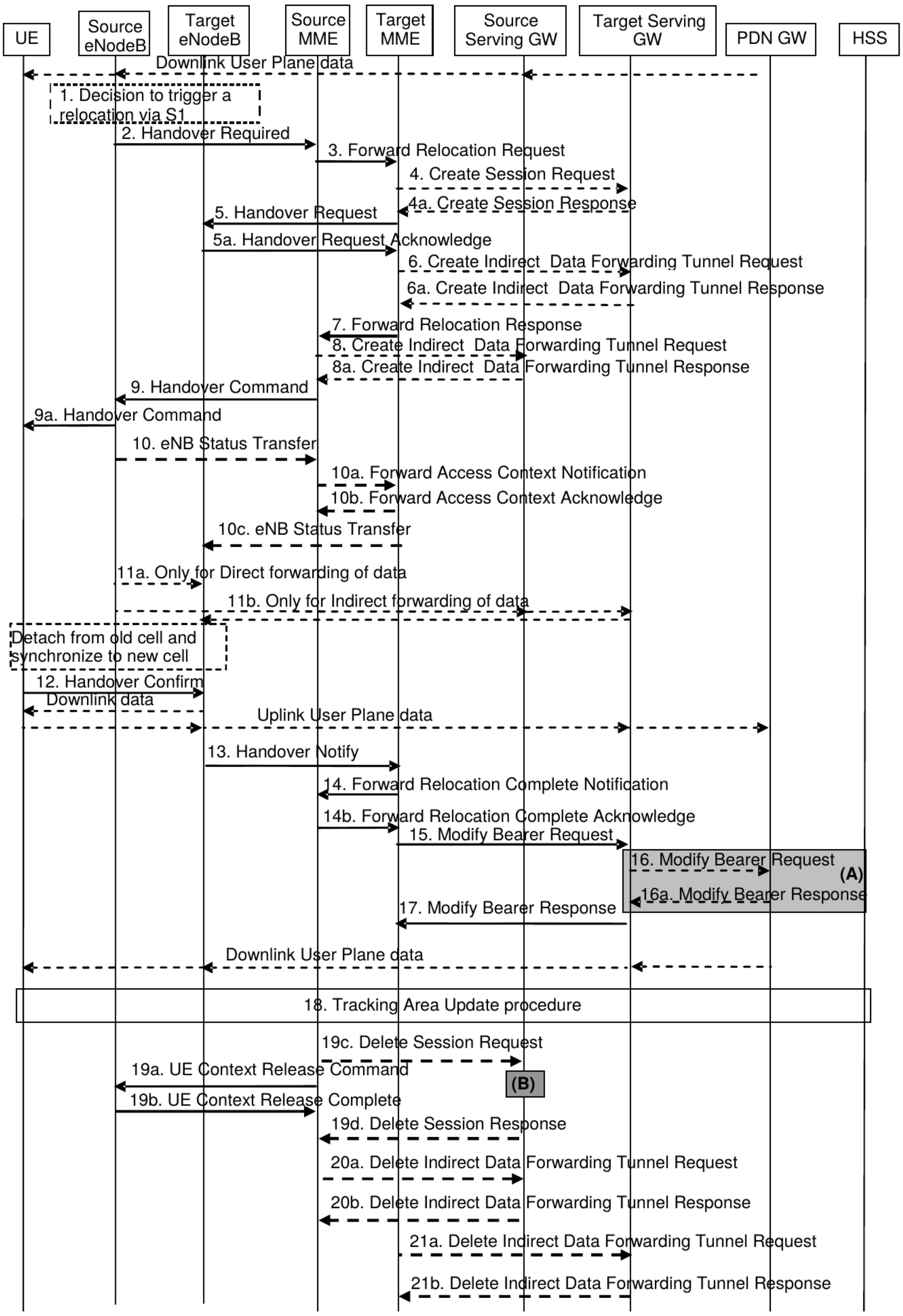


Figure 3.5 – LTE S1-based handover sequence diagram [124] in section 5.5

Network Discovery and Selection Function (ANDSF) [139, 140, 141], in order to facilitate and enable the seamless inter-RAT handover between 3GPP networks and non-3GPP networks. The ANDSF main feature is to assist the UE to discover non-3GPP access networks.

We have made a comparison of these two standards in the section 3.1.1.

3.1.1. Comparison between the MIH and ANDSF standards

The MIH (Media Independent Handover) protocol[8] is a standard framework that optimizes handovers between heterogeneous IEEE 802 systems and between IEEE 802 systems and cellular systems.

MIH is designed to maintain seamless mobility handover across heterogeneous wireless technologies. It was defined in 2009 and updated in 2017 [42], with a tutorial available in [142]. Generally, the main role of the MIH protocol is to assign information exchange that supports the topological and location information of service networks, neighboring networks, and the condition of the wireless links. It helps only in the handover initiation (searching new link, network discovery, network selection and handover negotiation) and handover preparation (setup new link, layer 2 connectivity). The MIH framework provides 802 components to other handover standards such as: Horizontal handovers for IEEE standards (IEEE 802.11r, 802.16e), IP mobility and handover signaling for IETF standards (MIP, SIP, HIP, FMIP, MIPSHOP) and Inter-working and handover signaling for 3GPP standards (SAE-LTE, I-WLAN).

MIH uses three key services to optimize the handover process as illustrated by figure 3.6. They are:

- Media Independent Event Service (MIES), which consists of link layer smart triggers and events related to the link changes (Link Up, Link Down, Link parameters change, Link Detected, etc), some predictive events (Link Going Down) and network initiated handover events (Load balancing, operator preferences, etc). This helps in achieving soft handovers and minimizes the disruption time.

- Media Independent Command Service (MICS), which provides handover messages and commands (Network initiated, Mobile initiated, vertical handovers) to control the link state.

- Media Independent Information Service (MIIS), which provides the network information such as the available networks (802.11 a/b/g/n/p, 802.16e, GSM/3G/LTE/4G/LTE-A), the neighbouring maps, networks services (ISP, MMS).

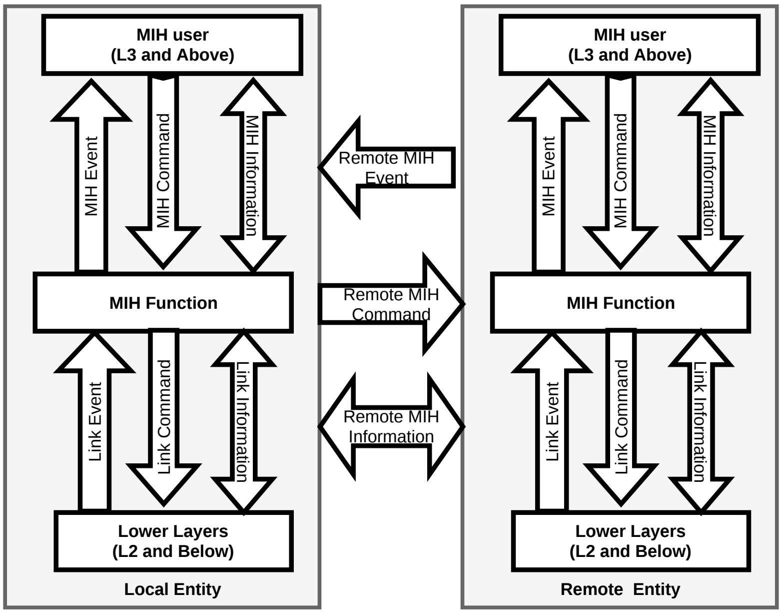


Figure 3.6 – Architecture of the MIH framework [114]

The MIH has been used in different researches in the literature such in [114, 90, 102, 101, 143, 115, 144, 145]. In [146], a comparison and review of handover decision schemes based on MIH and/or ANDSF (Access Network Discovery and Selection Function) have been given as illustrated by table 3.3. The parameters used for comparison were: the main objective, input parameters for VHO decision, additional entity, complexity, traffic, evaluation method and applicable area. Where FAF (Forward Authentica-

Table 3.3 – Comparison of seamless VHO enablers protocols standards: MIH, ANDSF

Category	Main objective	Input parameters for VHO decision	Additional Entity	Complexity	Traffic	Evaluation Method	applicable area
ANDSF (3GPP)	Minimal packet loss	not mentionned	FAF and/or DFF	Medium	video	Simulation	WIMAX-3GPP
MIH (IEEE)	Minimal packet loss, minimal latency, minimal call dropping, session continuity, best RAT	Multiple parameters	No need	low	IPTV, VoIP, CBR, FTP, Video	Empirical, testbed, simulation, analytical	WIMAX-GPRS, WIFI-UMTS, WIFI-WIMAX, WIFI, WIMAX and 3G, WIFI, WIMAX and UMTS
MIH& ANDSF	Minimal packet loss, Best RAT	Not mentionned	Combination (MIH/ ANDSF)	high	not mentionned	not mentionned	Wimax-LTE

[8] http://www.ieee802.org/21/

tion Function) was proposed in [140] and DFF (Data Forwarding Function) was proposed in [141].

From this comparison, it results that MIH is very appropriate in many kind of scenarios while presenting also a low implementation complexity than ANDSF. Another comparison between the MIH, ANDSF and IEEE 802.11u as enablers of seamless vertical handover standards is given in [43]. Note that despite these advantages of MIH, it do not specify which entity makes the handover decision or how the decision must be made (no standard algorithm for handover decision). The MIH only enables a cooperative handover decision making between the terminal (which collects measurements data and has measurement triggers) and the network operator (which stores the network maps and the services information in MIIS). In our thesis works, we have been inspired by these MIH features and we used them in combination with the PMIPv6, especially for the signaling task and disconnection detection task that are handled by the MAG in the PMIPv6 domain as we will see it in the following section.

3.1.2. Study of the support of PMIPv6 in LTE standards

First, we would recall that the general architecture of PMIPv6 protocol has been given in the figure 2.13. In order to perform the PMIPv6 functionnalities as described in section 2.5.3.2, the PMIPv6 entities (LMA and MAG) exchange the PBU (Proxy Binding Update) and PBA (Proxy Binding Acknowledgement) messages as illustrated in figure 2.13.

Thus, in cellular and 3GPP networks, the mobility support is defined in ETSI TS 123.402 [132] and the support of PMIPv6 [52] in those networks is well described in ETSI TS 129.275 [147]. From that, some features that PMIPv6 implements in LTE in addition to its classical functionnalities are:

- the IPv4 support for PMIPv6 which is defined in IETF RFC 5844 [148];
- the Generic Routing Encapsulation (GRE) [149] key option for PMIPv6, as described in details in IETF RFC 5845 [150],
- the Binding revocation for IPv6 mobility, defined in IETF RFC 5846 [151], and
- the PMIPv6 heartbeat mechanism defined in IETF RFC 5847 [152]

General mobility architecture models and concepts are given in TS 123.402 [132], in its section 4. They are based on the architecture reference model shown in the figure 3.7.

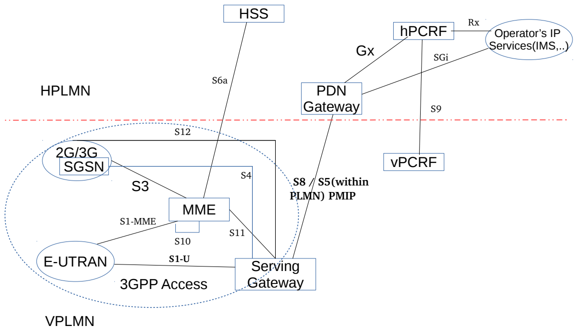


Figure 3.7 – Roaming Archicture for 3GPP accesses within EPS using PMIP-based S8 [132]

Hence in LTE, the PMIPv6 is generally applied between the Serving Gateway (SGW) and the PDN gateway (PGW) through the S5 or S8 interfaces, depending on whether the roaming is supported or not. When the support of roaming between different Public Land Mobile Networks (PLMNs) is available, the S8 interface is used for implementing PMIPv6, while S5 interface is used when there is no roaming. In both of these scenario, the SGW plays the role of a MAG node in PMIPv6, whereas the PGW becomes the PMIPv6's LMA node.

When a handover occurs and the connection between an UE and the PDN needs to be updated, the SGW node acting as a MAG initiates a PDN connection handover procedure. The steps of this procedure are as following:

- The MAG sends to the LMA, a Proxy Binding Update (PBU) message including the PDN's Access Point Name (APN) to which the UE might probably be connected after the handover.

- Upon the reception of PBU message, the LMA prepares the UE's PDN connection update.

- The LMA performs an IPv6 Home Network Prefix (HNP) or IPv4 Home Address (HoA) re-assignement (depending on whether IPv6 or IPv4 is used) by checking the address validity in the selected PDN.

- Both MAG and LMA establish downlink (DL) and uplink (UL) GRE keys to be used for GRE encapsulation of DL and UL traffic, respectively on the PDN connection.

- These GRE keys are then used in order to establish a GRE tunnel between the MAG and LMA. Both the UL and DL traffic that UE respectively sends and receives on the PDN connection are then captured and carried out from this established GRE tunnel.

- The LMA updates this Binding Cache Entry (BCE) by updating or creating this UE's PDN connection information in its local mapping table called Binding Cache.

- At this moment, the LMA sends to the MAG, a confirmation message called Proxy Binding Acknowledgement (PBA) which confirms that the binding update is completed. Note that if multiple PDN connections to the same APN function is supported by both the new MAG and the LMA, a PDN connection ID shall be included in both the PBU and PBA messages in order to take it into account.

- Thus, the new MAG (which becomes the new access point for the UE) creates a Binding Update List Entry (BULE) for this PDN connection

- When possible and upon the IP address(es) preservation decision, an IP address(es) preservation is made by reusing the IP address(es) which was (were) allocated in the previous initial attachment. The LMA also performs other re-assignement such as MAG Link Local Address re-assigment and UE Interface Identifier (IID) re-assignement in order to allow the formation of the same UE Link Local Address from the classic IPv6 link local address prefix (fe80::/64).

- For handover between 3GPP access and non-3GPP accesss (such as WIMAX, WLAN), the LMA may assign a possibly different alternate LMAA or IPv4-LMAA for LMA control plane Address and a possibly alternate LMA address for user plane. This is possible when those options are supported by both the MAG and LMA. However, for an intra-3GPP access handover, the LMA shall re-assign the same alternate (LMAA or IPv4-LMAA for Control plane and LMA address for user plane) address that was allocated during previous PDN connection establishment.

- Therefore, the LMA initiates the Update Notification procedure to notify the old MAG for handover with SGW relocation. Then, the old MAG triggers the generation of End Marker [147][section 5.11].

To illustrate some of other use-cases on how mobility might be handled in LTE using PMIPv6 (and possibly GTP and DSMIPv6), we give the figure 3.8 of 3GPP accesses with EPS using chained PMIP-based S8, s2a, s2b-Home

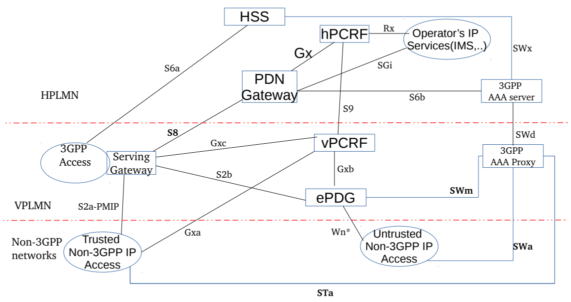


Figure 3.8 – Roaming architecture for 3GPP accesses with EPS using chained PMIP-based S8, s2a, s2b-Home Routed [132]

Routed by highlighting that more details could be found in respective standards: [132, 147].

In the table 3.4, we summarized the possible combination of IP mobility management selection handover between accesses and IP preservation procedures (ETSI TS 123.402)[132].

Table 3.4 – IP mobility management selection handover between accesses [132]

Networks / UE capabilities	**Supports**	**Selects**	**Handover types**	**IP preservation procedures**
NBM only		NBM	NBM (*)	S2a or S2b
DSMIPv6 only	No DSMIPv6	NBM	NBM by TN3 or ePDG	PMIPv6 or GTP specifications (**)
DSMIPv6	DSMIPv6	DSMIPv6	DSMIPv6 (TN3 or ePDG local IP as CoA)	S2c
DSMIPv6&NBM		NBM	NBM	S2a or S2b
DSMIPv6&NBM		DSMIPv6	DSMIPv6 (TN3 or ePDG local IP as CoA)	S2c
No capabilities indication		NBM	NBM	PMIPv6 or GTP specifications

Where NBM means networked-based mobility and TN3 means Trusted non-3GPP.

*: If prior to the handover, the UE was attached to a non-3GPP access with DSMIPv6, the handover scenario is considered not to be applicable.

**: 2 options of PMIPv6 IP preservation depending on the operator policies:

- preserve first IP based on timer, then assign new prefix after timer expiry
- Immediately assign a new prefix

Note that the UE capabilities information is made of the UE radio capability information and the UE core network capability information as specified in section 5.11 of [124].

The UE radio capability information contains information on RATs which the UE supports (e.g. power class, frequency bands, etc) and which are stored by MME during UE ECM-IDLE state in order to avoid overhead of periodic transmission of large quantity of information (e.g. $\geq$ 50 octets) through the radio interface and have to be updated when necessary.

Note also that the UE core network capability is split into the UE network capability Information Element (IE) (mostly for E-UTRAN access related core network parameters) and the MS network capability IE (mostly for UTRAN/GERAN access related core network parameters) and contains non radio-related capabilities, e.g. the NAS security algorithms, etc. Both of the UE network capability and the MS network capability are transferred between CN nodes when there are some changes like MME to MME, MME to SGSN, SGSN to SGSN, and SGSN to MME.

After that, we are now going to study in the following section, the main features that were added in the LTE reference architecture in order to support V2X services, which are the key challenging issues for vertical handover in VANETs.

3.2. LTE enhancements for V2X services support

In this section, we start by describing some scenario of V2X applications and use-cases, followed by their communications requirements. After that, we detail some LTE enhancements that are needed in order to fulfill those V2X support requirements in LTE.

Hence, many V2X scenarios and use-cases are given in TS 22.186 [153]. We have reported some of them in the table 3.5.

The requirements of these V2X applications have been also standardized and defined in TS 122.185 [155]. For illustration, we have categorized them as shown by the figure 3.9.

Table 3.5 – 3GPP Evolved V2X use-cases [3GPP TR 22.886] [154]

Use case group	Description
Platooning	It enables vehicles to dynamically form a group (platoon) travelling together. There is presence of a leading vehicle from which all the vehicles in the platoon receive periodic data in order to manage the platoon operations. In platoon, the distance between vehicles must be extremely small and this periodic information exchange may allow the vehicles following to be autonomously driven.
Advanced driving	It concerns semi-automated or fully automated driving in which each vehicle and/or RSU shares its own perception data, its driving intention and its data obtained from its local sensors with vehicles in proximity. This allows vehicles to coordinate their trajectories and helps in making safer traveling, collision avoidance, and improved traffic efficiency.
Sensor sharing	It is the exchange of raw or processed data gathered through local sensors or live video images and data among vehicles, RSUs, devices of pedestrians and V2X application servers. Thus, it helps in enhancing the vehicles' perception of their environment and giving them a holistic view of the local situation.
Remote driving	It enables a remote driver or a V2X application to operate a remote vehicle, especially for those passengers who cannot drive themselves or a remote vehicle located in dangerous environments. A high level of network and communication security is required in order to avoid driving hacking.

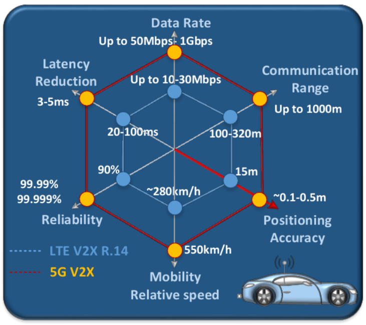


Figure 3.9 – C-V2X system requirements [156]

As noticed through the figure 3.9, V2X services are very critical especially in terms of latency, reliability, datarate and throughput. This is why since December 2015 in TR 22.885 [157, 158] and TS 22.186 [153], standardization organizations such as ETSI, 3GPP, 5GAA have proposed some amendments or extensions of the LTE standard architecture and functionalities in order to propose efficient manner to handle V2X services and communications in cellular networks (LTE, 5G).

This gave birth to a new LTE-V2X technology standard (first discussions took place in 2015) as an extension of the 3GPP Release 12 Device-to-Device (D2D) functionality, which is itself based on using the LTE uplink transmission and uplink spectrum resources for direct communication between devices. Thus, the basic safety V2V functionality specifications in the LTE technology were firstly released in the LTE Rel-14 specification [159].

Since then, many activities have been conducted in order to conceive and standardize the V2X communications in LTE as illustrated by the figure 3.10. We can cite the standardization of the Sidelink (PC5) interface which enables the support of the Proximity Service (ProSe) between vehicles.

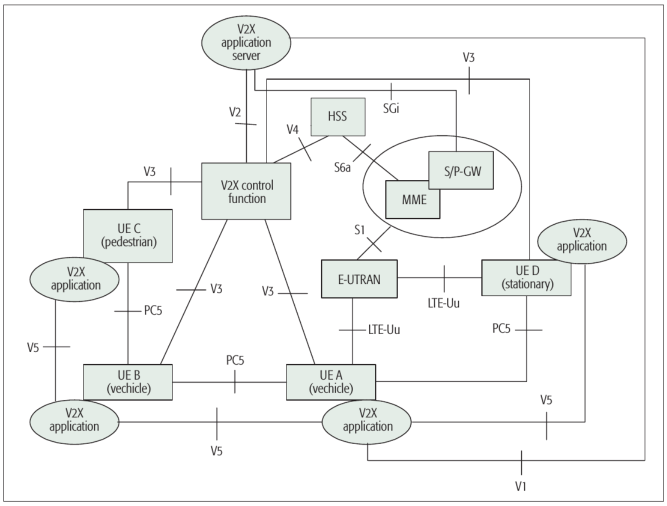


Figure 3.10 – Reference Architecture for LTE-Uu and PC5-based V2X communications in 3GPP [160]

Other main features that were added in this reference architecture (figure 3.10) are principally:

- the V2X control function which represents a logical function that is used for network related actions required for V2X.
- the V2X application server, which may support additional V2X related functionnalities such as providing the V2X USD (User Service Descriptions) for the UE to the above mentioned V2X Control Function, in order to receive the MBMS (Multimedia Broadcast Multicast Service)-based V2X traffic.
- Some other interfaces such as the V1 (between the V2X application and its application server), the V2 (between the V2X related application server and the control function), the V3 (between the V2X function and the Vehicle), V4 (between the V2X control function and the HSS) and the V5 (between V2X applications installed on different vehicles) interfaces.

More details on their specifications can be found in the section 4.3 of TS 23.285 [161]. Note also that the LTE main components (E-UTRAN, MME, SGW, PGW) are still available in this reference architecture.

Therefore, in order to address some of these required enhancements, the Release-14 LTE-V2X has introduced new Sidelink transmission modes (Transmission Modes 3 & 4) that we have described in table 3.6. Mainly,

Table 3.6 – LTE-V available modes description [159]

parameters / mode	**Scheduling method**	**channel access**	**use-case**	**Release**
Mode 1	eNB	eNB-controlled	public safety VoIP	LTE Rel-12
Mode 2	distributed	random, with blind re-transmissions	public safety VoIP	LTE Rel-12
Mode 3	eNB	eNB-Controlled	V2X	LTE Rel-14
Mode 4	Distributed	Sensing, with semi-persistent transmission	V2X	LTE Rel-14

these modes differ from Release-12 D2D modes (TM 1 & 2) by introducing the low-latency transmissions, the improvement of the support of high speed and the introduction of new distributed channel access mechanisms. Thus, the initial Cellular V2X (C-V2X) standard was completed late on September 26, 2016 [162].

A thorough study on the V2X services supported in LTE has been done by authors of [160]. They have also given an implementation proposal of these V2X services.

All those ongoing and aforementioned works are proof of more energy, enthusiasm and engagement in the LTE enhancements for V2X services support. However, there is still a need for many improvements tasks and challenges, and researchers are encouraged to go deeper in this field in order to propose and find efficient solutions needed for connected and autonomous vehicles deployment.

From this study, we found that efficient handover algorithms are still one of the open research topics that need further enhancements. In fact, these requirements such as high data rates, high reliability, lower latency, longer range, higher relative speed, accurate positioning, etc... are key metrics of V2X services that need to be continuously fulfilled and maintained in order to have acceptable V2X applications' performance. Unfortunately, there is actually no communications technology that can guarantee the maintainance of all of them continuously. This is why vertical handover algorithms are of great importance. During our thesis works, we have tried to take into account as much as possible these requirements. For that, we propose to take them as parameters inputs of our handover algorithms as it will be detailed in section 5.2, where we propose a tradeoff function betwen these applications requirements and the networks offering.

Clearly speaking, we wanted to have a method that can help in making decision based on multiple criteria, hence maximizing these requirements' fulfillment. Thus, we have found the Multiple Attribute Decision-Making (MADM) methods to be well adapted for handling these issues. That is why, we have continued our thesis work by studying the types of MADM that exist in the literature and that can be extended in order to be used in the vertical handover algorithms for heterogeneous vehicular networks (HVN) incorporating the LTE technology.

We are going to give an overview and description of these studied MADM methods in the next section 3.3.

3.3. Study of Multiple Attribute Decision-Making and processing methods: AHP and Fuzzy Logic use-cases

With the complexity of current systems and their operations, it has become more difficult to have more accurate methods of making choice between two or more complex systems' alternatives. This is due to the fact that, choice has to be always justified and high accurate in order to lessen the damage that may be caused by the made choice. This is the case of vertical handover in HVNs, where a best network must be chosen in real-time in order to ensure the best services' continuity when vehicles are moving from one network to another. For that, any decision must be taken by considering a lot of parameters. Therefore, the following questions must be always considered when designing a VHO algorithm: *"How does Vertical handover decision process works? What are the decision criteria used? How are gathered the needed criteria? what are the handover decision policies applied? Who is taking the decision, Mobile or network? What are handover performance optimizations that are possible?".* This leads to the complexity of decisions which will be proportional to the number of criteria and available alternatives.

Various Multiple Attribute Decision-Making (MADM) algorithms that tend to deal with this decision complexity have been proposed in the litterature. They could be seen principally as algorithmic ways of suitability that allow to realize the best network candidate selection and handover decision using different alternatives and their respective attributes.

In the litterature, different terms are used to express this type of decision methods. The frequent and most used terms are:

- Multiple Criteria Decision Making (MCDM): that are often applied in decision involving multiples objectives or multiple attributes, but generally when both apply.

- Multiple Objective Decision Making (MODM): that are applied in decisions where a set of conflicting goals cannot be achieved simultaneously
- Multiple Attributes Decision Making (MADM): that are applied when choosing an alternative (one goal) from a set of alternatives, characterized by many attributes.

3 components are often utilized in MADM algorithms [18]:

- the number of alternatives A with: $A = A_i, i = 1, 2, ..., n$
- The set of networks attributes/parameters C with: $C = C_j, j = 1, 2, ...m$
- Weight vector W with: $W = w_1, w_2, ..., w_m$ that takes the weight w_j of each parameter/criterion c_j.

We have already illustrated the position of some MADM algorithms in the handover process in the figure 2.9. Now, we are going to briefly describe the most used among them in section 3.3.1, then we will give details and litterature of the methods that will be used in our works (AHP and Fuzzy Logic) as well as our motivations to use them.

3.3.1. MADM overview

As previously said, many MADM algorithms have been proposed in the litterature. However, we have found that the popular MADM which are more used are:

1. Analytic Hierarchy Process (AHP): This type of algorithms is based on the divide-and-win paradigm. The main decision problem is divided into sub-problems, where each sub-problem is evaluated as a decision factor. AHP proceeds by constructing a decision hierarchy and compares each factor to all the other factors. Therefore, it calculates the sum of weights obtained from each levels of the hierarchy.

   From the set of alternative solutions, AHP finds the most optimal solution

2. Simple Additive Weighting (SAW): It consists in scoring and ranking all the alternatives. The overall score of a candidate is determined by the weighted sum of all the attribute values. Thus, for each alternative,

SAW adds each attribute value multiplied by its weight. Therefore, the alternative with the highest score is chosen as the best and most optimal candidate.

3. Multiplicative Weighting Exponent (MWE): MWE works like SAW algorithm with the only difference being that MWE uses the weighted product of all attributes' values instead of the weigted sum of SAW. However, since this product does not have an upper-bound, it is advisable to compare the score against an ideal solution.

4. Grey Relational Analysis (GRA): It is a mathematical algorithm that builds a grey relationship between the alternatives (networks). It considers one of them as with the ideal quality values and the rest of the alternatives are compared and evaluated against this ideal solution. The alternative that better approaches this ideal solution receives the highest score and will be chosen as the best candidate [103, 163] .

5. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS): Similarly to GRA algorithms, TOPSIS considers an ideal solution for performance comparison. Thus, it chooses the network that is the closest to the ideal solution and the farthest from the worst case [164].A comparison between Fuzzy TOPSIS and Fuzzy GRA is given in [165].

Others MADM algorithms (such as VIKOR, ELECTRE, DIA, ANP, etc) exist in the litterature and can be found in [14, 18, 44, 123, 166].

Performance comparison of some of these MADM has been given in [123]. Matlab functions for some of this MADM can be found at mathworks website[9].

We are now going to detail how the AHP and the Fuzzy Logic theory work, by giving also the motivation that guided us in using them in the vertical handover decision phase.

3.3.2. Analytic Hierarchy Process (AHP) litterature and motivation

According to its pioneer and founder Dr Thomas L. Saaty late in 1970s [5, 6], the Analytic Hierarchy Process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. For these reasons, it is largely used in a wide variety of decision situations

[9] https://www.mathworks.com/matlabcentral/fileexchange/65742-mcdm-tools?s_tid=FX_rc2_behav

around the world [7], especially in fields like governance, business [8, 9], industry [10, 11], healthcare and forecasting, transport [12], education, etc.

Using the divide-and-win paradigm, the main decision problem is divided into sub-problems, where each sub-problem is evaluated as a decision factor. In order to decomplexify the decision situation, AHP follows the decision process in hierarchy steps, taking into account the importance (weight) of each decision component versus another one, before arriving to the final optimal solution. This proves how AHP can be more benefitful in very complex situations, such as autonomous vehicles decision situations.

By helping to well understand the problem, AHP therefore provides a comprehensive and rational manner for structuring the decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and evaluating alternatives solutions.

This is the first reason that motivates us to test and use the AHP method for vertical handover decision making in VANETs. Furthermore, AHP has already been used in big companies and organizations such as :

- Microsoft, for quantifying the overall quality of their software systems
- University of Cambridge in order to decide where to locate offshore manufacturing plants [167],
- American Society of civil Engineers in assesssing risk in operating cross-country petroleum pipelines [168].
- AHP is taught in most business and administration schools
- In china, over one hundred universities teach AHP as decision method and over 1000 papers have been published using AHP [169] [10].
- In research, there is a specific international symposiun which deals principally with AHP: the International Symposium on the AHP. Authors of [166] employed the AHP for determining the relative importance of different parameters used in the VHO decision process. They also specified that the AHP trends to be the most popular method for VHO decision based on multiple attributes. In [170], AHP was combined to GRA in order to make an optimal selection based on time-vaying QoS information through cross-layer signaling. An overview of the AHP applications, listing more than 150 applications papers, is given in [7]. Authors of this paper have classified them in the following areas: personal, social, manufacturing sector, political, engineering, education, industry, government, sports, management, etc.

[10] http://www.isahp.org/2005Proceedings/

All those facts motivate us in using AHP as MADM method for vertical handover in VANETs.

Hence, the principal step of AHP are as follows:

1. Model the problem as a hierarchy of different levels constituting the goal, criteria, sub-criteria and alternatives as illustrated by figure 3.11.

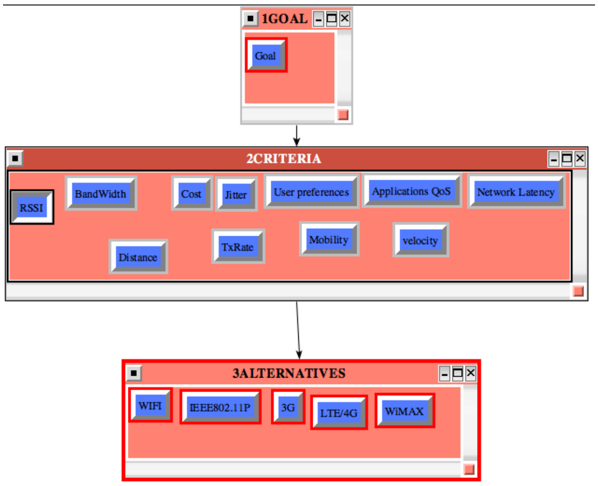


Figure 3.11 – Example of vertical handover decision architecture using AHP method

2. Establish a pairwise comparison between the elements at each level of the hierarchy: this step consists in establishing priorities among the previous defined hierarchy elements. This is done by making a series of judgements based on pairwise comparisons in order to rank the elements according to their respective importance (priorities) in fulfilling the goal. All the hierarchy's elements, except the highest element which must be the goal, must be compared to each others with respect to (w.r.t) each element at their high level. Thus, the criteria at the criteria level in figure 3.11 are compared to each others w.r.t the final decision (goal level). The alternatives are compared w.r.t the criteria as illustrated in figure 3.12. If available, sub-criteria are compared w.r.t criteria, and so on. This pairwise comparison is mostly based on two questions: *which of the two elements is more important with respect to a higher level criterion?, and how strongly?*[5]. Note that this requires $n(n-1)/2$ comparisons for a matrix of order n, where n is the number of elements, while considering that diagonal elements

are equal to "1" and the other elements will simply be the reciprocals of the earlier comparisons [5, 7].

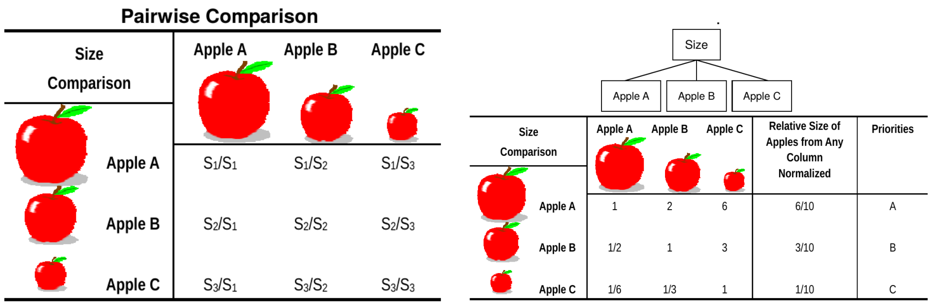


Figure 3.12 – Example of reciprocal structure of pairwise comparison matrix for 3 apples with respective size S1, S2, S3. Extracted from [5]

3. Synthesize the resulting judgements in order to have a set of overall priorities for the hierarchy (priorities for each criteria at each hierarchy level).

4. Check the consistency of the judgements. This consistency is checked by calculating normalized values (weight) for each criteria/alternative, the Consistency Index (CI), and the Consistency Ratio (CR). The CR must be less than a given threshold (0.1 by default). Otherwise, the pairwise comparison must be modified and the procedure repeated till the CR is under the specified threshold.

5. Choose the best alternative based on the final result of this process.

Mathematically, this process results in the following steps:

1. Develop the weights for the criteria by:

    - firstly, developing a single pairwise comparison matrix for the criteria,
    - then, multipling the values in each row together and calculating the n^{th} root of this obtained product,
    - after that, normalizing the aforementionned n^{th} root of products to get the appropriate weights;
    - finally, calculating and checking the consistency ratio (CR)

2. Develop the ratings for each decision alternative for each criterion by:

- firstly, developing a pairwise comparison matrix for each criterion, with each matrix containing the pairwise comparisons of the performance of decision alternatives on each criterion
- then, multiplying the values in each row together and calculating the n^{th} root of said product,
- thus, normalizing the found n^{th} root of product values to get the corresponding ratings
- finally, calculating and checking the consistency ratio (CR)

3. Calculate the weighted average rating for each alternative, then choose the one with the highest score.

However, some extensions and variation in the normalization have also been proposed. Fuzzy AHP extensions has been used in [171, 172, 8] and can be found in [7].

> *Scale of measurement are inventions of a technological mind, since the number of things we don't know how to measure is much larger than the things we know how to measure, and it is highly unlikely that we will ever find ways to measure everything on a physical scale with a unit because, unlike physical things, most of our ideas, feelings, behavior and actions are not fixed once and for all, but change from moment to moment and from one situation to another*[6].

Thus, as the key step to AHP is the pairwise comparison step, a unified comparison *scale* has been proposed and refered to as the *fundamental scale* of the AHP[5]. It is illustrated by the table 3.7.

This table 3.7 relates the fact that the dominance of the largest object in the pairwise comparison must be no more than 9 times the smallest one, which is the widest span used for many good reasons in the AHP litterature. Mathematical functions and process details of AHP can be found in [5]. AHP method and other MADM are also described in [173, 13, 7, 44, 166].

3.3.3. Fuzzy Logic litterature and motivation

Most of the parameters'values that are used in the decision phase for vertical handover in IoV come from sensors. Therefore, due to the vehicles'speed, the gathered information is often imprecise with high degree of uncertainty. Furthermore, the fact that many parameters must be used in vertical handover, computational algorithms are very important and are frequently used in the decision phase.

Table 3.7 – Comparison scale values

Positive Value	**Description**	**inverse Value**	**Description**
1	Equally preferred	1	Equally preferred
2	Equally to moderately preferred	1/2	Equally to moderately non-preferred
3	Moderately preferred	1/3	Moderately non-preferred
4	Moderately to Strongly preferred	1/4	Moderately to Strongly non-preferred
5	Strongly preferred	1/5	Strongly preferred
6	Strongly to very Strongly preferred	1/6	Strongly to very Strongly non-preferred
7	Very Strongly preferred	1/7	Very Strongly non-preferred
8	Very to Extremely strongly preferred	1/8	Very to Extremely strongly non-preferred
9	Extremely preferred	1/9	Extremely non-preferred

To handle this issue of uncertainty of the gathered information, fuzzy control theory and neural networks techniques are often applied. Usually, these algorithms are applied first in order to convert imprecise data into precise ones. Afterwards, a MADM algorithm is fed with these data to determine the best choice [13]. In [14, 15, 16], authors precise the importance of using fuzzy logic in vertical handover. They specified that Fuzzy Logic (FL) and/or Neural Networks (NN) concepts are applied to choose when and over which network to hand over among different available access networks. Fuzzy logic can be combined with the multiple criteria or attribute concept in order to develop advanced decision algorithms for both non-real-time and real-time applications. **They pointed out that classical MADM methods can not efficiently handle a decision problem with imprecise data that the decision criteria could contain. For that, the use of FL is not only to deal with imprecise information but also to combine and evaluate multiple criteria simultaneously. Hence, FL concept provides a robust mathematical framework in which vertical handover decision can be formulated as a Fuzzy MADM.**

Like said by authors of [16], we found that it is intuitive to use fuzzy logic in situations with uncertainty, as it is in our case of VANETs field, thanks to its aforementioned inherent strength in solving problems exhibiting imprecision.

Fuzzy Logic controllers functionning

The fuzzy logic is based on controllers set called Fuzzy Logic controllers (FLCs). Each FLC is composed of the following steps:

- Fuzzification: it is a step to determine the degree to which an input data belongs to each of the appropriate fuzzy sets (e.g: low, medium, high) via the membership functions (MFs) (e.g. gaussian, triangular, ramp, zshape, etc) [17]. The membership functions are defined mathematically with several parameters.

- Inference engine system (FIS): this FIS processes the fuzzified inputs and correlates them to the outputs using "IF....THEN...." rules, which are predefined in the rule base as a knowledge database. Note that each rule results to a certain degree for every output, expressed as membership degree and calculated using a predefined membership function (e.g. gaussian, triangular, ramp, zshape, etc).

- Aggregation: After the inference, the output degrees for all the rules of the inference phase have to be aggregated (using a predefined Aggregation operator). This gives a fuzzified output.

- Defuzzification: the fuzzified output from the aggregation is defuzzified using one of the available defuzzifier methods (e.g. MinOfMax, Centroid i.e center of gravity, etc) in order to have the final discrete output value for the decision making process.

The fuzzy logic theory highly improves the accuracy and reliability of decision made with most fluctuating and uncertain values.

The special features of fuzzy system considered to other system using the traditional logical (binary true or false) are that:

- Fuzzy logic introduces a degree of uncertainty, which allows it to handle uncertain values, contrary to traditional logic which uses exact values (difficult to have in a frequent changing environment such as VANETs)

- Fuzzy logic manipulates well imprecise terms, which are normal to human language. Thus, fuzzy system works not only with binary logic, but it also mimic human thinking (which is very achieved with deep learning in AI)

- Fuzzy logic simplifies the design of complex systems, which are well present actually in almost every domain with the advent of the Internet of things in general, and particularly the Internet of Vehicles (IoV).

- Fuzzy logic is able to process information in subjective way (allowing to consider qualitative parameters such as QoS, QoE, etc), which is different from the traditional logic which deals only with quantitative data.

- Fuzzy logic values are available in the range [0-1], while the traditional logic uses the binary set of $\{0,1\}$. This allows to affect intermediate values from 0 (exclusion) to 1 (full membership) to the degrees of relevance (membership) of a term.

The functionning of fuzzy logic can be summarized as follows: Input parameters are fed into a fuzzifier that converts them into fuzzy sets by determining the degree to which they belong to each of the appropriate fuzzy sets via membership functions. Next, the fuzzy sets are sent to a fuzzy inference engine for the application of IF-THEN rules to attain fuzzy decision sets. The output fuzzy decision sets are accumulated into a single fuzzy set and delivered to the de-fuzzifier for conversion to an accurate quantity in final stage of the handover decision [18].

In litterature, many works [174, 16, 175, 176, 177, 178, 179, 180] have used fuzzy logic as a method for handling imprecise data and/or as a MADM-based method. Furthermore, from the vertical handover methods classification in [18], it resulted that fuzzy logic is an ideal tool for dealing with uncertain cases, when the inputs are rough estimated data values, with frequent fluctuation changes [177].

We have therefore considered the AHP method and the fuzzy logic in our works, for the reasons that have been detailed in their respective subsections.

3.4. Conclusion

In this chapter, after a long study of handover protocols in the LTE-based systems, we have seen how the decision phase is very complex and need to be well designed in order to have a reliable and efficient vertical handover. Therefore, we have studied some of the most popular MADM methods. Then, we have presented an overview of these methods in this chapter. We have particularly highlighted the advantages of the AHP method in handling multiple attributes based decisions and the advantages of the Fuzzy Logic theory in dealing with problems using uncertain or imprecise data.

In the next chapter, we will present our proposed Vertical handover approach that we called PMIP-based Mobile Internal Vertical Handover. After that, we will see how we applied these MADM methods in order to propose efficient handover algorithms in the HVN domain.

Chapter 4

PMIP-based Mobile Internal Vertical Handover (PMIP-MIVH)

After this deep review of existing handover solutions, we concluded that despite their advantages and their different manner of handling the handover's steps, the paramount and common problem stills to find the most suitable time to trigger the handover and minimize the handover latency and handover impact. Indeed, the VANETs' high level of mobility and their dynamic change in the topology make very difficult to predict how long the vehicle will stay connected to a network since this prediction might be based on a lot of parameters (such as velocity, direction, traffic flow, network signal, the distance between the vehicles and the RSUs, signal interference, obstacles interfaces, multipath fading, transmission range and transmission power, transmission power gain, Service Level of Agreement (SLA) sensibility, user preferences, QoS, etc). Albeit this prediction difficulty, most of the existing solutions were still relying on the Received Signal Strength Indicator (RSSI) measurement, before deciding to trigger a handover. This always conducts to a critical disconnection time, often referred to as handover latency. This has a negative impact on the application's performance such as the loss of packets. The latter might be harmful to some types of applications such as safety and realtime applications. We have considered this difficulty to have a good and accurate method to predict how long the vehicle will stay connected to a network, and we analyzed the consequences of the disconnection time during a vertical handover in critical applications such as autonomous driving. Therefore, we focused on how we can reduce this disconnection time and its negative impacts. That is why, in order to answer to the *When* issue, we have proposed our vertical handover mechanism denoted Proxy MIPv6-based Mobile Internal Vertical Handover (PMIP-MIVH) [19] that we present in this chapter 4. Our PMIP-MIVH approach consists in a direct and simultaneous mobile connection to any available new type of networks while stills connected to the current one. Therefore, our method results in an anticipation of the next potential mobile handover and it is based on a soft and efficient use of a logical interface. Thus, numerical model analysis show that our proposed solution (PMIP-MIVH) performs well in terms of handover connection durations, handover latency and session continuity. Consequently, our method allows to reduce the handover latency and reduce/avoid as much as possible the packet loss, and therefore increases the overall system's throughput.

In this chapter, we will start by describing our approach in section 4.1. Then, we will present its analytical model and its cost analysis in section 4.3. Finally, comparison results for our proposed PMIP-MIVH approach will be discussed in section 4.4.

4.1. Our proposed approach: PMIP-MIVH

In our approach, we considered the following assumptions, illustrated by the figure 4.1:

- We are in a context of heterogenous vehicular network, which means that we often have more than one network (otherwise, no need for handover because whether we directly connect to the only available network or we are completely disconnected),

- Possibility of soft handovers: Our target is to be always connected at least to 2 networks, when available, as usually used in datacenters (redundant networks),

- The MN does not wait to be disconnected before it reconnects to another network (use of multiple network devices on every vehicle or mobile),

- In order to make redundancy, we want to use the diversity by duplicating the flow on the different available physical interfaces by mimicking the flow mobility extensions,

- Finally, we take advantage of distributed PMIPv6 for architectural purposes.

In such scenario, every vehicle must always be connected to, at least, one network. Thanks to soft handover, a vehicle can also be simultaneously connected to multiple networks, by using multiple RAT devices installed on every vehicle. Following the PMIPv6 flow mobility extensions specifications and by using logical interface, we can reduce handover latency and packet loss. Hence, we can ensure QoS and increase the throughput and the load balancing by making just a mobile internal handover (RAT switching), which

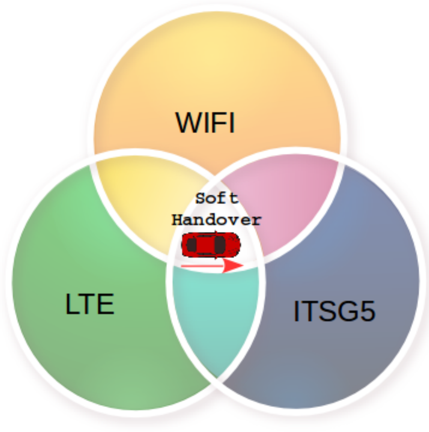


Figure 4.1 – Context of the proposed approach

lasts few time. This is because it has to take place within the mobile. Thus, there is no long distance delay and we gain time by anticipating all new address configuration while MN is still connected to at least one other network. Those are the most aspects that we considered when proposing our PMIP-MIVH approach.

Practically, we want the logical interface to play the role of data transmission and data reception, while the multiple physical interfaces play the role of signaling, radio access and control plane. This is the signaling part (*Initiation*) of the handover process that we wanted to anticipate. This step is done using the distributed PMIPv6 approach and it is illustrated in figure 4.3 as *"Immediate Connection using PMIPv6"*. Therefore, the MAG is responsible of handling the L2 handover steps at this stage within our PMIP-MIVH method. Thereafter, when the mobile needs to receive data, it will firstly check the availability of the connectivity by calling the *interface::IsUp* method (which implements the selection and decision phase of the handover) of the logical interface. This method consequently triggers the method *IsUp()* on each installed physical interface. This method *IsUp()* on physical interfaces was inspired from the ones proposed by the Media Independent Event Service (MIES)[42, 142]. Using the OR conjuction, it checks whether at least one interface is up (which means that its RSSI is high enough to receive packets) on the mobile. This selection and decision phases are represented as *"Find remained Up interface"* in figure 4.3. Thus, the pseudo-code in algorithm 1 illustrates this process.

If at least one interface is connected, therefore the mobile can receive data without wondering whether the corresponding physical interface is down or not. This is possible thanks to the possibility of establishing a reception

Algorithm 1 Find Up Interface

-- N=number of devices

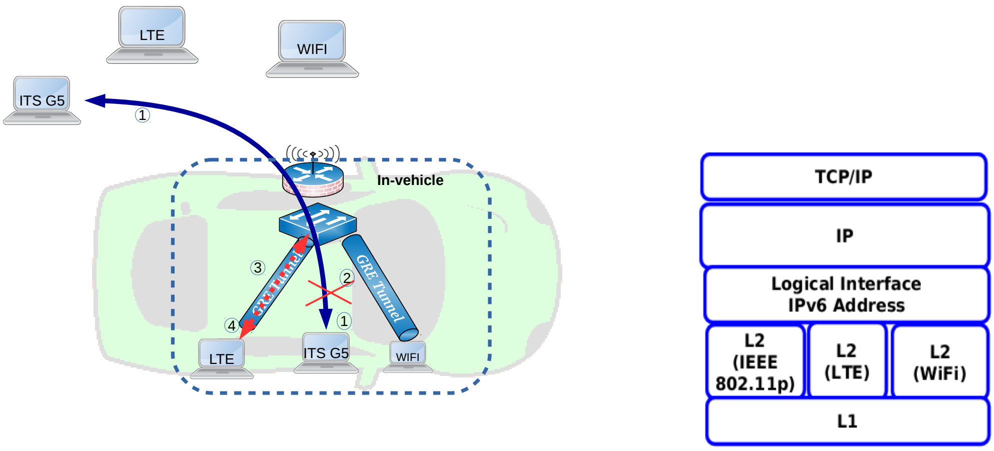
Require: $N \geq 2$;
  $interface = 0$
  $UP = []$
  for ($i = 0; i < N; i \leftarrow i + 1$) **do**
    if ($IsUp(i)$) **then**
      $UP \leftarrow UP \cup i$
    end if
  end for
  $interface$ = choose candidate interface in UP vector
  Create Tunnel with $interface$ to Receive packet

tunnel between the logical interface and each up interface. In other general situations, it might firstly trigger the handover process at this time in order to handle the data reception. **This is where we gain and improve the handover latency and the throughput, compared to other available solutions**. Therefore, the communication with the remote correspondent can continue even if there might have been occured changes in the physical interface states. When receiving data, the logical interface can lookup to the up interfaces on which it can route the received data. By this method, we can ensure that the session continuity is guaranted thanks to the logical interface functionnalities.

This needs that we design a virtual tunnel or bridge to route packets within the mobile itself. We have opted for the use of Generic Routing Encapsulation (GRE) tunnels as described in RFC 2784 [149] and updated by RFC 2890. In other words, we want to make a L4-to-L2 port mapping which will allow us to route the upper layer packet to a corresponding RAT network type and also will allow us to perform the vertical handover just by switching the RAT technology only inside the mobile, exactly at layer 2. We have illustrated this approach within figure 4.2 and we denote this approach Mobile Internal Vertical Handover (MIVH).

Apart from being viewed as a simple network interface by the host IP layer and upper layers (such as the application layer), the logical interface has specific properties that are essential in vertical handovers (handover between multiple access networks) which are:

- possibility to have a relation to a set of physical interfaces on the host that it is abstracting or hidding their existence
- Possibility to be attached to multiple access technologies
- Dynamicity of connection and attachment with the pysical interfaces,



(a) (b)

Figure 4.2 – Proposed Mobile internal vertical handover architecture. (a) Implementation architecture inside the vehicle. (b) Logical interface location in the TCP/IP model.

which consequently become sub-interfaces when attached to logical interfaces (heritage)

- a dynamic mapping between transmission/reception functions of logical interface with the Transmit/receive functions of physical interfaces.

- Maintenance of a IP flow information for each of its attached pysical interfaces.

All those properties help the logical interface to hide the presence of multiple physical interfaces on the mobile side (vehicle), hidding consequently all changes (that are monitored by using the MIES feature of MIH), which take place at lower layers among the physical interfaces. This is essential for a transparent and seamless vertical handover.

Therefore, we have proposed the algorithm illustrated by the flowchart presented in the figure 4.3.

In this figure 4.3, we show how our approach works. It is launched when the mobile starts and it is not connected to any network interface. Then, when it arrives in the coverage of the first available network, it simply connects to it in the usual way. At this time, it becomes connected to one network and apply the Best Effort principle. Then, the mobile has to monitor for other potential networks to which it can connect using the MIH standard principle [42, 145]. If available (which means that the Received Signal

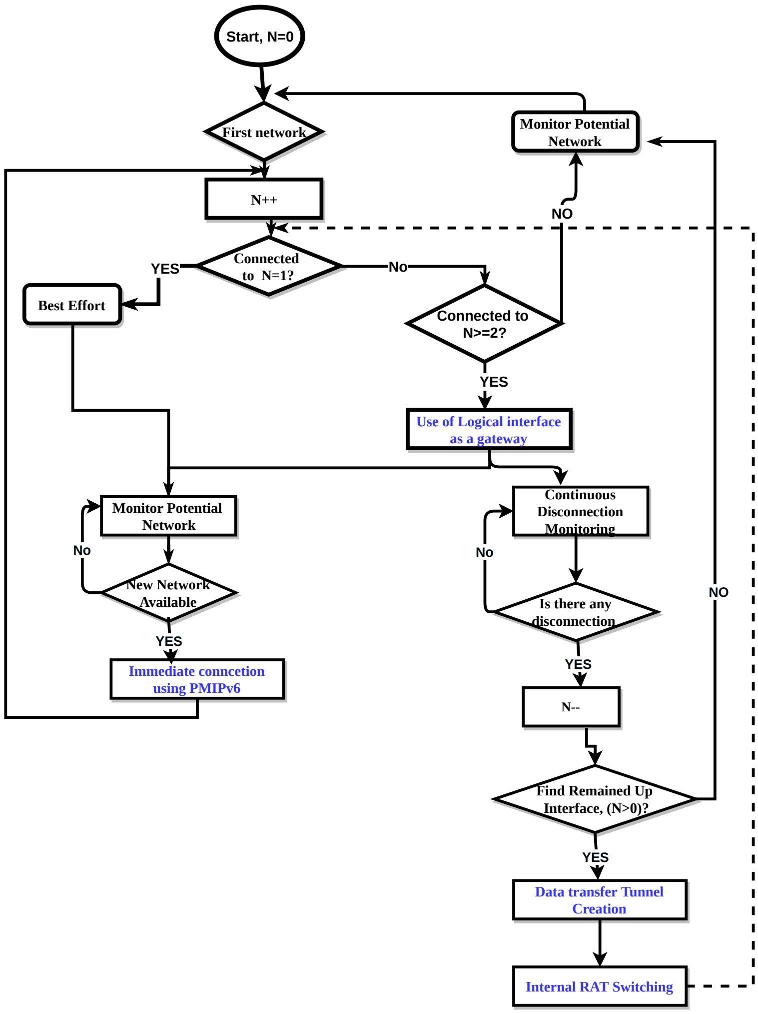


Figure 4.3 – Flowchart of the algorithm of the proposed PMIP-MIVH approach

strength Indicator (RSSI) is higher enough to be connected to this network), we have to anticipate the potential next handover process, while remaining connected to the current network. Reason why, the mobile directly connects to it and becomes connected at least to two networks.

The fact of being connected to two networks or more can be exploited in order to maximize the probability of receiving packets, when one interface goes down. This can be achieved by asking the logical interface to ensure the redundancy of a received packet after a detection of a disconnection of one of the physical interfaces by duplicating the received messages on the available physical interfaces. When implemented, this feature might help in increasing the packet delivery ratio and also the throughput. This is also possible because in our use-case (VANETs), we assume that the battery or energy are less restrictive than for other networks such as mobile phones or sensors in WSN. This is why we consider that, being simultaneously connected to multiple network will have no more impacts on the battery life and therefore the connection duration.

Since we just connect to the new network but we do not directly trigger a handover, we also avoid the ping pong aspect. This is because, even when the mobile did not last in the new network, it remains connected, at least, to one other network, so no more handover proccess is needed. We have just to well route the affected flow which was attached to the RAT which becomes disconnected (for example LTE device at step 2 in this figure 4.2a) and route it to the remaining connected RAT (ITS G5 or WLAN, at step 4 in the same figure 4.2a). For that, it firstly creates a tunnel (GRE tunnel) done in step 3 at this figure. The selection of the best candidate network could be done using a suitable Multiple Attribute Decision-Making (MADM) method such as fuzzy logic or Analytical Hierarchy Process (AHP) in order to verify their respective QoS capability and respect the user QoE and Service Level Agreement (SLA). Thanks to our logical interface, which always presents one HNP to the host IP layer and serves as a gateway to external network outside the vehicle, all this process takes place only inside the mobile node (vehicle) in layer 2, without loss of IP session conectivity. This proves that the mobile communication and session will be kept and guaranted to other correspondents. We have, then, reduced all the handover latency, the packet loss and the message overhead that were produced when exchanging messages between LMA and MAGs. All packets from external networks (WiFi, LTE, ITS G5) will be delivered whether their respective link type is up or down.

4.2. Pratical and applications use-case: Remote self-driving monitoring and information collection

In order to test our proposed approach, we considered the use-case of remotely collecting information for autonomous driving car monitoring. For that, we have a data center which collects real time information about a self-driving car. When data are received within this remote server located in the traffic center office, traffic agent can analyze them and alert the passenger in the driving car in case of self-driving car deficiency (data alerting from sensors, possible loss of connection, weather problem, GPS inaccuracy, battery discharges, path prediction error, etc).

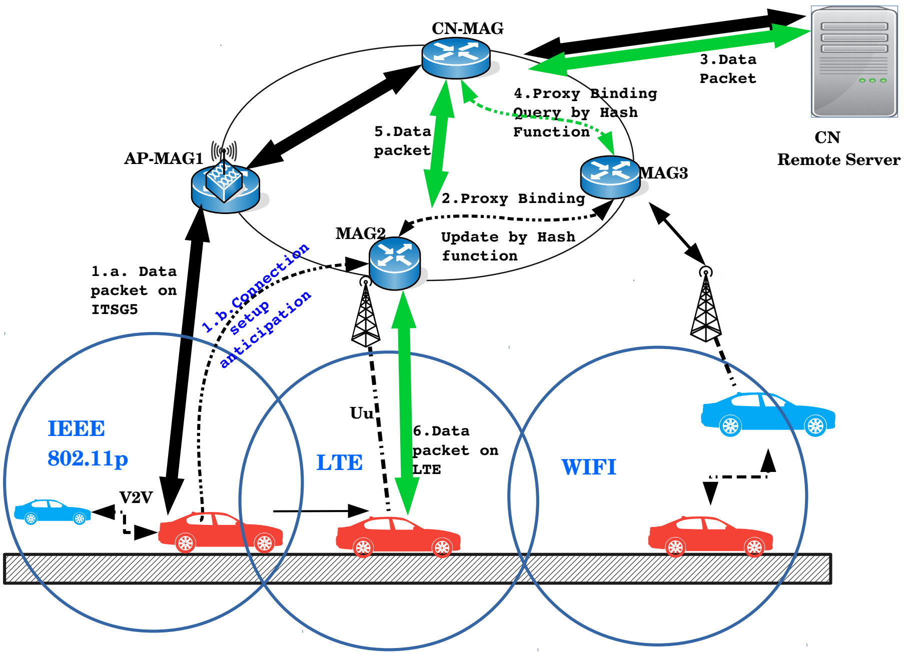


Figure 4.4 – Applications use-case architecture

In order to test the applicability, we have performed simulation using NS3 and results show that packets destined to LTE device are well delivered and received through the ITS-G5 device when the LTE device becomes down and vice-versa. Analytical results are detailled in section 4.4 while simulation results are discussed in section 6.3.2.

4.3. Analytical model and cost analysis

We used the model described in [62], where performance in terms of costs of some DMM scheme were analyzed, to perform our approach measures. The extended model is illustrated by figure 4.5, where the correspondent Node (CN) represents a static remote server and the Mobile Node (MN) is the mobile vehicle which will need to perform a handover. This cost is related to the total cost required for binding update with LMA and for data packet delivery from CN to MN. In [62], authors have compared two existing schemes (PMIP and PMIP-LR) and their three proposed schemes i.e. Signal-Driven PMIP (S-PMIP), Data Driven Distributed-PMIP (DD-PMIP), and Signal-

Driven Distributed PMIP (SD-PMIP). Authors of [61] have also proposed a Hash based PMIPv6 solution. We compared our approach to their solutions.

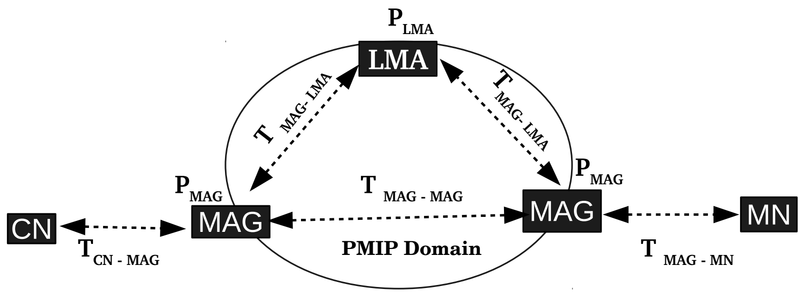


Figure 4.5 – Network model for numerical analysis [62]

The parameters used in this cost analysis are described in the table 4.1, whereas their respective values used in the analytical comparison are given in the table 4.2.

Table 4.1 – Description of Parameters used for cost analysis

Parameters	**Description**
T_{a-b}	Transmission cost of a packet between nodes a and b
P_c	Processing cost of node c for binding update or lookup
T_{setup}	Setup time of PMIP connection between MN and MAG
$N_{Host/MAG}$	Number of active hosts per MAGs
N_{MAG}	Number of MAGs in the PMIP domain
H_{a-b}	Hop count between nodes a and b in the network
$S_{control}$	Size of control packet (in bytes)
S_{Data}	Size of control packet (in bytes)
α	Unit cost of binding update with LMA
β	Unit cost of lookup for MN at LMA or MAG
τ	Unit Transmission cost of a packet per a wired link (hop)
κ	Unit Transmission cost of a packet per a wireless link (hop)
δ	Unit cost of hash operation at MAG
μ	Unit cost of new MN address or HNP configuration

4.3.1. Cost analysis

The cost analysis for the classical PMIPv6 is detailed in [61] and is given as follows:

The Binding Update Cost (BUC) is equal to:

$$\begin{aligned} BUC_{PMIP} =& T_{setup} + S_{control} \times 2T_{MAG-LMA} + P_{LMA} \\ =& T_{setup} + S_{control} \times 2\tau H_{MAG-LMA} \\ &+ \alpha log(N_{MAG} \times N_{Host}) \end{aligned} \tag{4.1}$$

and the Packet Delivery Cost (PDC) is expressed as:

$$\begin{aligned} PDC_{PMIP} =& S_{data}(T_{CN-MAG} + 2T_{MAG-LMA} + T_{MAG-MN}) \\ &+ P_{LMA} \\ =& S_{data}(\kappa H_{CN-MAG} + 2\tau H_{MAG-LMA} \\ &+ \kappa H_{MAG-MN}) + \beta log(N_{MAG} \times N_{Host/MAG}) \end{aligned} \tag{4.2}$$

Then, we get the Total Cost (TC) by summing the BUC and the PDC as follows:

$$TC_{PMIP} = BUC_{PMIP} + PDC_{PMIP} \tag{4.3}$$

Following the same philosophy, the binding update (step 2) which takes place between the new MAG and the intermediate MAG (respectively MAG2 and MAG3 in figure 4.4) takes at least two control messages (PBU/PBA). Therefore, the BUC_1 of PMIP-HD is expressed as:

$$BUC_1 = S_{Control} \times 2T_{MAG-MAG} + P_{hash} + P_{MAG}, \tag{4.4}$$

where:
$T_{MAG-MAG} = \tau H_{MAG-MAG}$,
P_{hash} is the processing cost of Hash function using MN-Home Address (MN-HoA) at MN-MAG and P_{MAG} is the processing cost for binding update to the designated MAG. Therefore:
$P_{hash} = \delta log(N_{Host/MAG})$ and
$P_{MAG} = \alpha log(N_{Host/MAG})$

The signalling operation for binding query (step 4) which takes place between the CN-MAG and the intermediate MAG (MAG3 in figure 4.4) when CN have a data to sent to MN, also takes 2 control messages (PBQ/PQA) [62]:

$$BUC_2 = S_{Control} \times 2T_{MAG-MAG} + P_{hash}(\text{at CN-MAG}) + P_{MAG} \tag{4.5}$$

Therefore, we obtain that the total Signalling Control Cost (SCC) of PMIP-HD is equal to:

$$SCC_{PMIP-HD} = BUC_1 + BUC_2 \tag{4.6}$$

which gives us:

$$\begin{aligned}SCC_{PMIP-HD} =& T_{setup} + 2 \times (S_{control} \times 2T_{MAG-MAG}) \\ & + 2 \times (P_{hash} + P_{MAG}) \\ =& T_{setup} + S_{control} \times 4\tau H_{MAG-MAG} \\ & + 2\delta log(N_{Host/MAG}) + (\alpha + \beta) log(N_{Host})\end{aligned} \quad (4.7)$$

and the packet Data Delivery Cost (DDC) of PMIP-HD is given as:

$$\begin{aligned}DDC_{PMIP-HD} =& S_{data}(T_{CN-MAG} + T_{MAG-MAG} + T_{MAG-MN}) \\ & + P_{MAG} \\ =& S_{data}(\kappa H_{CN-MAG} + \tau H_{MAG-MAG} \\ & + \kappa H_{MAG-MN}) + \beta log(N_{Host})\end{aligned} \quad (4.8)$$

Thus, the total cost of PMIP-HD becomes:

$$TC_{PMIP-HD} = SCC_{PMIP-HD} + DDC_{PMIP-HD} \quad (4.9)$$

In our approach (PMIP-MIVH), we reduced this cost by anticipating the connection setup time T_{setup}, and by eliminating the new address configuration time μ in the handover process by using the proposed logical interface. Therefore, our P_{MAG} (for binding update to the designated MAG) becomes

$$P_{MAG} = (\alpha - \mu) log(N_{Host/MAG}) \quad (4.10)$$

That gives that the handover Signaling Control Cost of our approach becomes:

$$\begin{aligned}SCC_{PMIP-MIVH} =& S_{control} \times 2T_{MAG-MAG} + P_{hash} + P_{MAG} \\ & + S_{control} \times 2T_{MAG-MAG} + P_{hash} + P_{MAG} \\ =& S_{control} \times 4\tau H_{MAG-MAG} + 2\delta log(N_{Host}) \\ & + (\alpha - \mu + \beta) log(N_{Host})\end{aligned} \quad (4.11)$$

and the packet Data Delivery Cost is the same as of PMIP-HD:

$$DDC_{PMIP-MIVH} = DDC_{PMIP-HD} \quad (4.12)$$

Then, we get the Total Cost of our approach, denoted $TC_{PMIP-MIVH}$, equals to:

$$TC_{PMIP-MIVH} = SCC_{PMIP-MIVH} + DDC_{PMIP-MIVH} \quad (4.13)$$

4.4. Numerical analysis

In order to validate our approach, we have compared our proposed solution PMIP-MIVH to the classical PMIPv6 and the PMIP-HD solutions. For simplicity, we only considered the PMIP-HD in the category of distributed mobility management (DMM) candidates because it has already been compared to the other DMM schemes in [61], where it shows that it outperforms them. We have chosen to measure the performance in terms of: the setup time impact on the total cost, the impact of the number of hosts per MAG and the impact of binding update cost in order to test how much our solution is scalable, and finally the impact of the distance represented as the hop count between the PMIP entities (LMA and MAGs). The parameters values are reported in the table 4.2. All results are expressed in Unit Cost.

Table 4.2 – Parameters values used for cost analysis

Parameters	**Default**	**Minimun**	**Maximum**
$T_{setup(ms)}$	100	200	500
$N_{Host/MAG}$	200	100	1000
N_{MAG}	20	10	100
$H_{MAG-LMA}$	5	1	10
H_{MN-MAG} H_{CN-MAG}	1	1	1
$S_{control}(bytes)$	50	50	50
$S_{Data}(bytes)$	1024	1024	1024
α	3	1	10
β	1	1	10
τ	1	1	10
κ	4	1	10
δ	1	0	2.0
μ	2	1	2

Figure 4.6 shows the impact of the setup time on the total costs. It can be clearly noticed that the classical PMIP has the highest total cost (figure 4.6a). Thus, its total cost is up to 51666.4 against 14828.1 for PMIP-HD and 14323.5 for PMIP-MIVH when the setup time T_{setup} is 500 ms. We added the figure 4.6b in order to higlight the improvement of our approach compared to PMIP-HD. Thanks to our anticipation of this setup time, our approach has the lowest total cost and the handover is not anymore impacted by this time as it is the case for other schemes. Through this figure 4.6b, we notice that when the time T_{setup} increases, the total cost remains constant in our proposed approach while the total cost of PMIP-HD increases proportionally to the

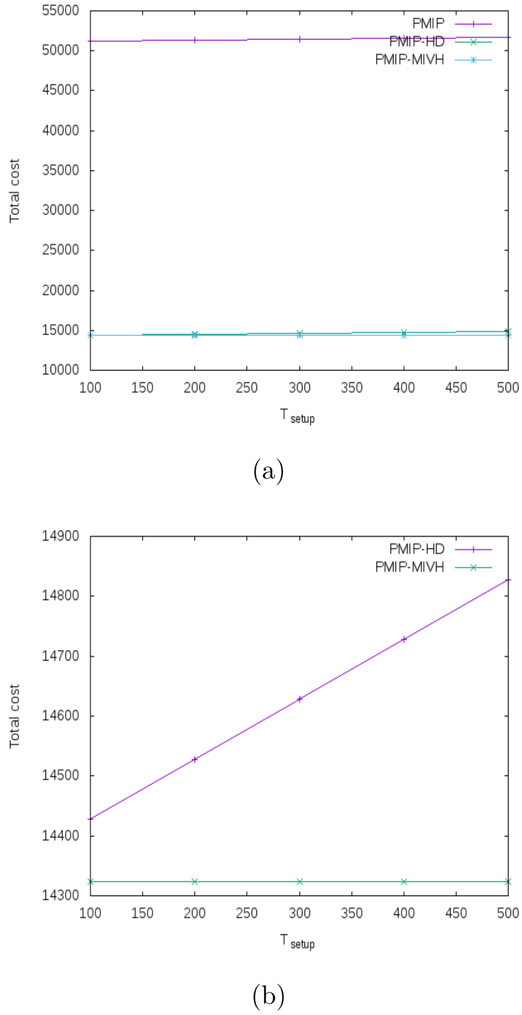
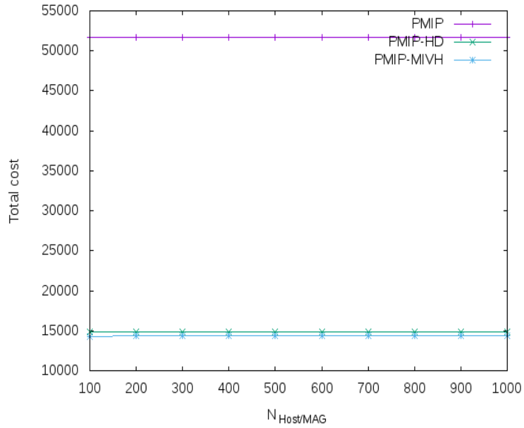


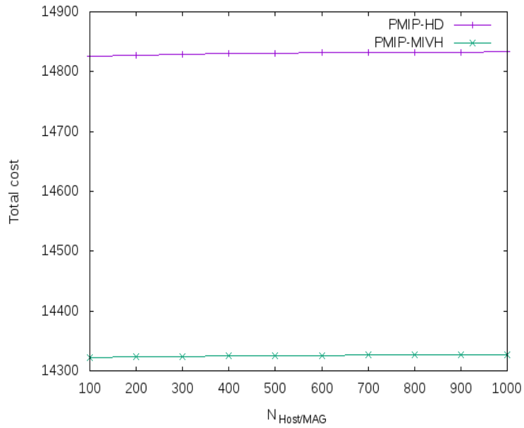
Figure 4.6 – (a) Setup time impact on the total cost. (b) Zoom of the Setup time impact between PMIP-HD and PMIP-MIVH.

T_{setup}. This proves that by anticipating this setup time, we can improve the handover performance. Therefore, our approach represents a 3.40% of improvement compared to the PMIP-HD and up to 72.27% compared to PMIP, when T_{setup} equals to 500 ms.

Figure 4.7 shows the impact of the number of host per MAG $N_{Host/MAG}$, which therefore increases the BUC in log scale. It shows that our approach is well adapted to high number of hosts and presents a 3.41% of improvement compared to the PMIP-HD and 72.2% compared to the classical PMIP. Here also, we used figure 4.7b in order to higlight the performance of our approach compared to PMIP-HD. This results highly depend on the Binding Cache



(a)



(b)

Figure 4.7 – (a) Impact of the number of hosts per MAG on the total costs. (b) Zoom of impact of the number of hosts per MAG between PMIP-HD and PMIP-MIVH.

design, which influences the lookup time. The increasing of the curves is not linear and is not proportional to the increase of $N_{Host/MAG}$, thanks to our consideration of using an optimal BC design like a hash table or a Balanced Binary Search Tree (BBST) using a hash function [1]. That is why, we use the log scale of $N_{Host/MAG}$ in the total cost analysis equations in section 4.3.1. Other optimal BC designs might be achieved by using other optimal search designs such as optimal binary search tree [2]) in which the search

[1] http://www.ilikebigbits.com/2016_08_28_hash_table.html

[2] https://www.gatevidyalay.com/time-complexity-of-bst-binary-search-tree/

operation time is in a log scale of the number of stored hosts on the MAG. Therefore, the difference is not noticeable until when $N_{Host/MAG}$ represents a high exponential value with base 10.

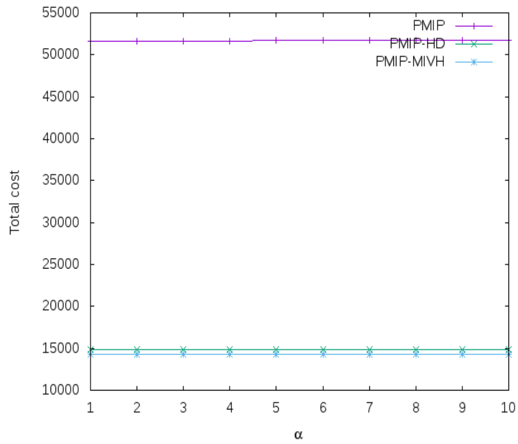


Figure 4.8 – Alpha value impact on the total costs

Figure 4.8 shows the impact of the Binding Update Cost. It shows that our approach benefits from the use of the logical interface and the presentation of only one HNP to IP layer in order to reduce, in average, about 3.39% and 72% the binding impact compared to PMIP-HD and PMIP, respectively.

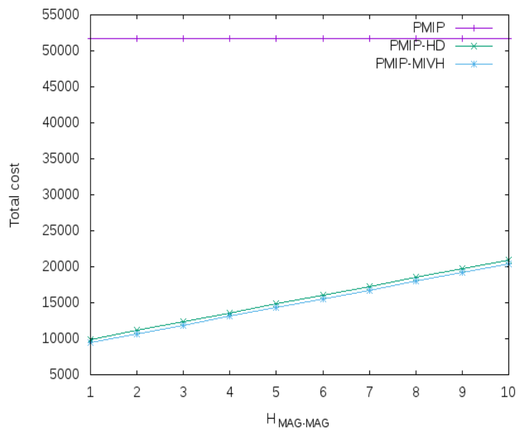


Figure 4.9 – Hop count between MAGs impact on the total costs

Figure 4.9 shows that the increasing of hop count between MAGs has a high impact on the total cost in PMIP-HD and in our approach, while it has a constant impact in PMIP. However, our approach performs better than PMIP-HD with an average difference of 504 (unit cost). Therefore, PMIP stills have the highest total cost even though it remains constant. This shows the advantage of Distributed Mobility Management (DMM) approaches compared to centralized mobility management approach. Furthermore, we can notice that when $H_{MAG-MAG}$ equals to 10, the total cost of the PMIP-HD solution and our approach starts to double the total cost compared to $H_{MAG-MAG}$=1. In the figure 4.10, we show that the hop count between

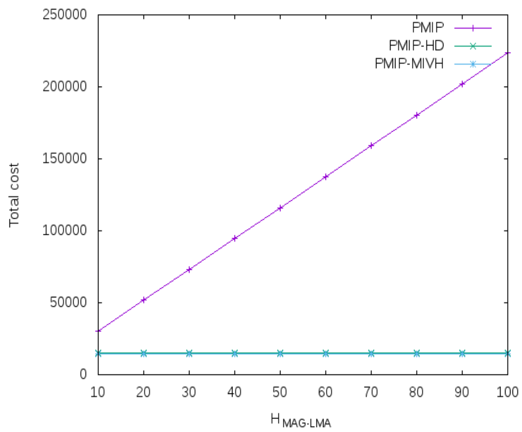


Figure 4.10 – Hop count between LMA and MAG impact on the total costs

LMA and MAG drastically impacts the total cost in PMIP due to the centralized traffic through the LMA, which also impacts the scalability of the whole network. However, it shows that our approach has similar performance as PMIP-HD, because they both benefit from the distributed architecture, and therefore, there is no traffic which passes through the LMA.

4.5. Conclusion

In this chapter, we have seen how our PMIP-based MIVH aproach works and we give an example of an application use-case in which we applied our vertical handover mechanism. We have also proposed an analytical model and discussed its numerical results which prove that our solution improved well the handover process.

In addition, our approach can be extended in order to well perform the traffic load-balancing by routing different flows through different networks,and hence increasing the quality of service (QoS) and user experience (UX) by taking into account the network user preferences and bandwidth when filtering the traffic flow if possible. This will improve the global throughput of the system. Otherwise, the best effort could be applied by default.

In the following chapter 5, we will address the *where* issue by using the AHP MADM method and Fuzzy Logic theory that we have already described in section 3.3. After that, we will present the implementation of these solutions in chapter 6.

Chapter 5

Proposition of candidate network selection algorithms and methods in VANETS

In the previous chapter, we have answered to the *"When"* vertical handover issue by proposing the PMIP-MIVH method. Now, in this chapter 5, we are going to answer to the *"Where"* issue by proposing two types of algorithms of selecting the best network candidate for vertical handover.

Thus, we will start by proposing an AHP-based method in section 5.1. We will also discuss some limitations of this AHP-based method. Then, in section 5.2, we will define our expected QoS metric by proposing a tradeoff function between the application requirements and the service offered by each available network. Finally, we will propose a fuzzy-based algorithm denoted PMIP-FL using the defined expected QoS metric in section 5.3.

5.1. AHP-based network candidate selection method

For the purpose of proposing a selection method of the best network candidate, we have firstly proposed to use the AHP method thanks to its advantages as described in section 3.3.2. For that we have proposed the hierarchy illustrated by figure 5.1 for vertical handover selection method in VANETs.

As illustrated, 3 main levels are present in this hierarchy: Goal, Criteria, and Alternatives. In the second step, we made pairwise comparisons between these criteria with respect to the goal in order to get the weight vector containing the weight of each criteria. For that, we used the fundamental scale in order to compare each criteria to another with respect to the goal. Then, we made pairwise comparisons between the alternatives with respect to each criteria. To achieve that, we used one of the well-known AHP software called SuperDecisions, which has been developed by the enterprise founded by Thomas L. Saaty, the pionner and founder of the AHP method. An illustration of one of these pairwise comparison is given in figure 5.2.

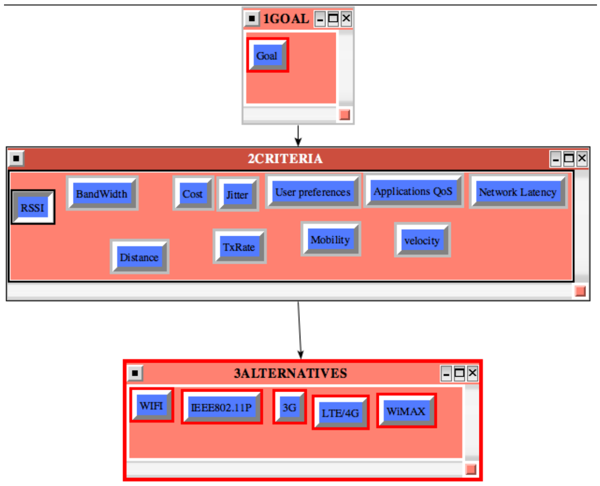


Figure 5.1 – Proposed hierarchy architecture for the AHP-based vertical handover approach

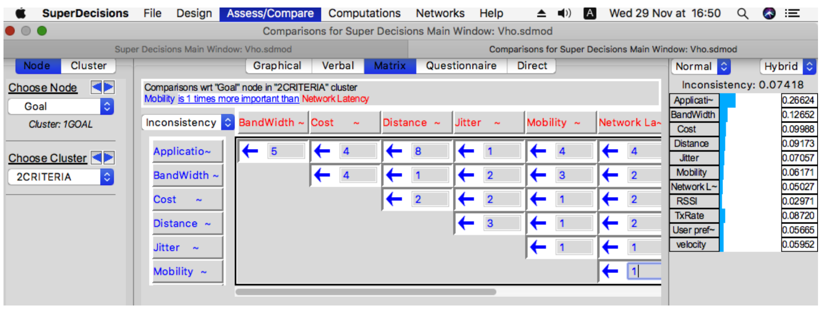


Figure 5.2 – Illustration of the AHP pairwise comparison between criteria

For each comparison, a corresponding matrix is created. Note that for every pairwise comparison, the consistency ratio must be checked in order to have a consistent system at the end of the pairwise comparison processing also refered to as the rating process.

The following step was calculating the supermatrix by combining these comparison matrix using multiplication in order to have the final matrix that contains the resulting weight of each criteria. The final step is about synthesizing this supermatrix and normalizing the results, which gives the correponding score for each alternative as illustrated by figure 5.3.

In this figure 5.3, we can see the final classification of the available alternatives with their corresponding rating (ideal values and normalized values). In this scenario, we see that the 3G was ranked as the best network with a score of 0.276, followed by the LTE (4G) network with a score of 0.225, then the IEEE 802.11P with a score of 0.208, the WIFI with a score of 0.1544

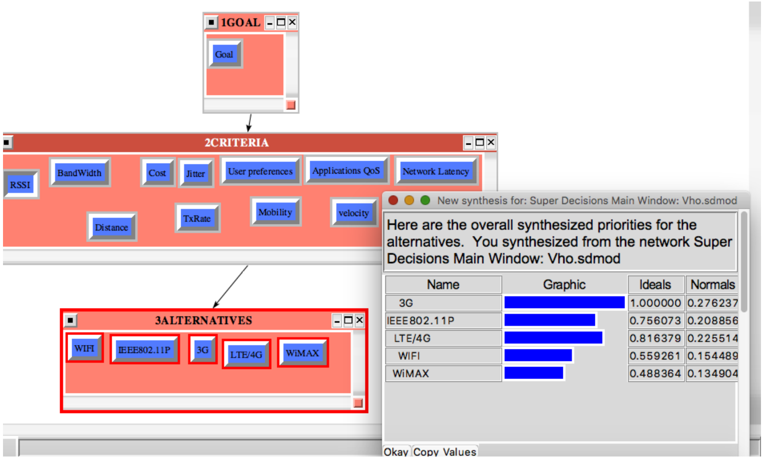


Figure 5.3 – Overall synthesized priorities of the alternatives for the considered hierarchy.

and finally the WIMAX with a score of 0.134. However, these results are only true according to this tested scenario and are difficult to be generalized. The AHP results are very dependent on the weight that has been assigned to each criteria or alternative during the pairwise comparison. Hence, they become user/designer dependent. Due to this user/designer specific dependancy, a good experience and an expertise in the field in which AHP is used is required in order to design the system. Furthermore, in many cases, many decision-makers have to be taken into account.

Thus, we noticed the following AHP shortcomings:

- The core part of AHP is based on the pairwise comparison matrix. One of the problem of AHP is that if the pairwise comparison is not well correlated, depending on the psychology state of the decision-makers or their experience, all the decision-making can be worse.

- AHP demands a high expertise and experience in the problem specific domain in order to get accurate comparison, which might be difficult for designers and engineers that want to have an efficient system with more parameters as possible. Which is the case in the trending topics such as autonomous driving cars deployment.

- AHP decision comparison process tends to be more static and appropriate for decisions that do not have to change frequently and quickly.

This can be seen from the types of applications cited in section 3.3.2, in which AHP was often used. Therefore, it is most useful for projects management involving teams of people (government law, financial planning, new product design and implementation, etc), giving their judgements/perceptions on the decision criteria and alternatives. This is the case of planning and strategic decisions whose resolutions have long-term repercussions.

- Furthermore, the comparison terms used in the AHP comparison process might be ambiguous or with different values from one decision maker to another. This might lead to no consensus in the decision process. For this issue, we suggest to use instead the fuzzy logic theory.

Above of that, we have not found open source project developing AHP implementation or an integration library in C++; in order to use it for example in NS3. For that, AHP is mostly used in private developed tools that are not open. Therefore, this makes very difficult the integration of AHP-based solutions in the network simulation tools, for the sake of reproductivity of these solutions and their comparison with other proposed solutions. This has directed us to test other methods with available open sources that can be easily extended and integrated in simulation tools in order to benefit from the simulations' advantage before deployments. For that, we looked for an other most used approach in such complex systems, and we have selected the fuzzy logic for its benefits and advantages, especially in handling the same psychological dependent decisions as AHP, given that even the comparison terms in AHP method were already somehow fuzzy. For these above shortcomings, we have opted to test and use fuzzy logic which helps to smoothly reduce the comparison ambiguity and use linguistic variables, which are close to the human psychology and human thinking, in describing complex systems' structure and functionning.

5.2. Proposition of the Expected QoS tradeoff function

In [13], authors emphasize on the issues of QoS and QoE definition. They also precise that guaranteeing the QoS is not enough in order to provide the best possible service to users. Thus, the Quality of Experience (QoE)[20] is a conceipt related to the users' satisfaction which ties together the user perception, experience and expectations with non-technical and technical parameters such as application- and network-level performance, typically expressed by quality of service (QoS) [21]. A QoE assessment sometimes evidences that good networking performance (IETF view of QoS) is not a synonym of total satisfaction to the end users (ITU-T view of QoS [20]). From the observation that, generic QoS problems (e.g. packet loss, delay, jitter, throughput limitations, reordering) imply obviously generic QoE problems (e.g. artifacts, excessing waiting times, glicthes), an exponential relationship between the QoS and QoE, refered as IQX (exponential Interdependency of Quality of eXperience and Quality of Service) hypothesis, was given by Fiedler et.al. in [21] and is expressed as:

$$QoE = \alpha \times \exp^{-\beta.QoS} + \gamma \tag{5.1}$$

With the QoE parameter representing the level of satisfaction and the QoS parameter reflecting the level of disturbance. Thus, the QoE parameter and user perception decrease when the QoS parameter increases.

This formula is a solution to the equation

$$\frac{\partial QoE}{\partial QoS} \simeq -\beta.(QoE - \gamma) \tag{5.2}$$

stipulating that the change of QoE depends on the current level of QoE, given the same amount of change of the QoS value, but with a different sign [21]. An optimal fitting function determining the α, β, γ values for VoIP service was calculated by authors of [181], using the matlab optimization toolbox. For packet loss parameters, they affected the values 3.010, 4.473 and 1.065 to α, β, γ , respectively, while for jitter parameter, the values 2.482, 10.453, 1.141 were respectively assigned.

For the QoE value, the Mean Opinion Score (MOS) is used in order to have the value range of [1-5][21].

Note also that, a user centric algorithm that uses a throughput threshold ratio tradeoff, the channel occupancy estimation, the measurement of dowlink SINR was also proposed in [57], whereas a QoE-efficiency perspective that aims on evaluating the performance of MADM was proposed in [182]. Furthermore, a VoIP QoE is described in [183, 20].

From this background and observation, we see that the user preferences, the application requirements and the network capabilities must be taken into account in order to design an efficient VHO strategy and technique. Therefore, we designed a tradeoff function that we called Expected QoS tradeoff function which takes into account some of the QoS technical parameters (bandwidth, packet loss, delay, jitter), whose degradation might directly imply the QoE degradation.

For that, we adapt and extend the generic VHO function proposed in [184] by using those parameters (bandwidth, packet loss, delay, jitter) as illustrated by figure 5.4:

We also considered these parameters as they are the most frequent parameters that constitute the minimum QoS requirements (which directly will impact the QoE) of each application[1]. Even though each application requires different values for these parameters. However, many times, the minimum value with respect to each of these parameters must be known before starting the application. Likely, these parameters values may remain constant/static during a given time at their minimum required value and the application might continue to work properly.

Therefore, in order to have the QoS (and consequently the expected QoE's component) metric for each network, we decided to calculate them regarding the type and requirements of the application. For that, we propose to make a pairwise comparison between the application requirements and the performance of each network. For that, we defined a function f which calculates for each considered parameter, the ratio $\frac{ApplicationRequirement}{NetworkOffer}$ between each application requirement and the respective capabilities provided by the network. Note that, in order to avoid to divide by zero, a parameter whose network offer equals to zero is not considered for that network. It is ignored by assigning it a weight of zero.

The expected QoS tradeoff formula becomes:

$$QoS_i = (a \times f(BW), b \times f(PDR), c \times f(Jitter), d \times f(Latency)). \tag{5.3}$$

Where a, b, c, d are numerical values that represent (and are proportional to) the importance of the respective parameter in the QoS tradeoff function and consequently, in the whole vertical handover decision.

Hence, in order to have a good QoS, we must increase the bandwidth (BW) and therefore, the PDR. Subsequently, we have to diminush, as much as possible, the jitter and the latency.

Note that the total of these weight values must be equal to 1. Thus,

$$a + b + c + d = 1. \tag{5.4}$$

This allows a flexibility of our system. In fact, our tradeoff function can be extended and could take few or more parameters, since a missing parameter will be disqualified by giving it a weight value of 0. Saying that, we have to increase the a, b values, and decrease the c,d values. Another observation is

[1] https://en.wikipedia.org/wiki/Quality_of_service

that if the signal represented by the RSSI is good, the following situations are probable :

- when we have a sufficient bandwidth, the PDR might be good in ideal case.
- With a good bandwidth, the jitter will be also lower, because there are no other more influencing parameters if we have enough resources (expressed by the available bandwith in wifi and the number of available Resource Blocks (RBs) in cellular networks.)
- With a good bandwith, the latency may stay constant or still depending only on the distance and the speed (Round Trip Time).

With this assumption and being in safety applications, we have to highly prioritize the bandwith, then the PDR. Furthermore, the jitter and latency will be taken into consideration because of the real time effect of the applications. However, those weight values could be designer-specific and might be corrected according to the type of application, the experience and the expertise of the system's designer.

We must be aware that the QoS is a combination of different parameters, expressed in different units. The use of ratio values helps us to deal with this problem. Thus, we decided to express the QoS in a relative way as a qualitative parameters according to the Mean Opinion Score (MOS) values in [21]. Therefore, we defined a corresponding fuzzy parameter and use it in the fuzzy inference system, alongside with the RSSI and Speed.

Therefore, we consider cross-layer parameters with: PDR, bandwidth, jitter, and latency at the application level and the network level, then, the RSSI at the physical layer level and the speed for vehicle related parameter.

Therefore, our contribution of using fuzzy logic is many fold:

- In contrast to traditional handoff approaches which are based on one (RSSI) or few parameters, we have used a reasonable number of parameters that we thought are very important in order to have a more accurate decision.
- In order to have an efficient processing system, we have diminushed the number of fuzzy parameters in order to have an acceptable and computable number of rules in our Fuzzy logic controllers.
- In order to have a good end-user experience, we have defined our QoS metric by defining a tradeoff function between the user preferences, represented by the applications' requirements, and the service offered

by the network. We, therefore, base our decision mechanism on this tradeoff. This can enhance the whole quality of service offered to the customer at any time.

In order to have the range value of QoS, which represents the possibility of having different value of QoS (low, medium, good, high), every QoS subcomponent must have the range or number of units.

For example, for PDR, we know that it can not be over 1 (100%), thus a unit might be equivalent to 0.1. Thus, the total PDR units become 10 units.

This might allow us to compare the service offered by each network regarding the PDR. For example, if WiFi PDR is 0.5, LTE PDR is 0.45, ITS-G5 PDR is 0.8, we can say that in terms of PDR, Wifi have 5 units, LTE has 4.5 units and ITS-G5 has 8 units. Therefore, the ITS-G5 is the best network in terms of PDR.

For many parameters, it might be difficult to have the maximun available values (e.g., bandwidth), depending on the whole capacity of the network and the number of active users and active applications at a given time. This also influences the availability of other parameters values (e.g., jitter, latency) which depends on the number of users and applications served by the network. Therefore, it becomes difficult to get the maximun values to be used in the formula in order to know the maximun units. For the sake of simplicity, we suppose that the maximun needed value for these specific parameters (bandwidth, jitter, latency) is equal to the double of the applications requirements. This is just to ensure that we have enough resource for the application with no possible impact regarding this parameter. Therefore, the maximun bandwidth of the network becomes expressed as :

$$BW_{RequiredMax}(i,j) = 2 * Max(BW_{app(j)}) \tag{5.5}$$

Where $i = 1, 2, ..., n$ and $j = 1, 2, ..., m$, n= Number of networks, and m= number of applications on the network. This is also applicable to other parameters. However, it is to be noticed that the the maximum value expresses the best scenario for parameters with positive impact (such as bandwidth), while it represents the worst case for parameters with negative impact such as the jitter, and latency.

5.3. Fuzzy Logic-based algorithm: PMIP-FL

According to simulation comparison of 8 MADM algorithms done in [123], in which they concluded that the Fuzzy-based MADM is the best algorithm for background, conversational and streaming traffic, and concluding also that there is no MADM algorithm that is most appropriate for all traffic classes, we have, therefore, chosen to design an application-based algorithm by :

- using the fuzzy logic to deal with uncertainty
- being inspired by the divide-and-win paradigm of the AHP when weighting alternatives, and
- using SAW as a ranking method for the alternatives

Based on AHP working model, the whole problem (Goal) of finding the best network is divided into sub-problems (for each network, pairwise comparison of each application's requirement with the respective network parameter with respect to the good working way of this application.). So, the system is designed in the object-oriented paradigm. Thus, it is composed of sub-modules as illustrated by figure 5.4. Each sub-module corresponds to an influential component of the global decision.

The figure 5.4 illustrates our fuzzy logic based vertical handover mechanism design. It is an Application-RAT-capabilities-tradeoff-based fuzzy logic system for Vertical handover in HVN. In order to use more parameters for accurate vertical handover, we designed this cross-layer approach by taking into consideration the application's requirements. We created our QoS metric expressed in terms of the ratio between the offer of each available RAT compared to the application's requirements. Thus, we started by comparing application parameters with the capabilities offered by each available network. For that, we have to use the tradeoff function defined in equation (5.3), which may be common or specific to each available network, in which we apply a division (if no zero values are present). The difference can be also used by calculating the absolute values of the difference between each application requirement parameter values and the respective parameter values offered by each network. This gives us a value for our defined QoS metrics. This is what we called as the application-RAT-capabilities tradeoff.

To be more reactive to every fluctuating situation, we prefered to use fuzzy logic. Therefore, we have designed a Fuzzy inference system (FIS) for each RAT. We used 3 parameters as input, which are : RSSI, speed and QoS for both ITS-G5 and wifi networks as they have similar properties. For LTE, the RSSI is not a good parameter for handover decision, therefore we used the RSRQ instead of RSSI. We also use the QoS and speed as well for LTE FIS inputs.

For more details about data gathering and data measurement for this parameters in the simulation, see data gathering implementation sub-section A.2.2.

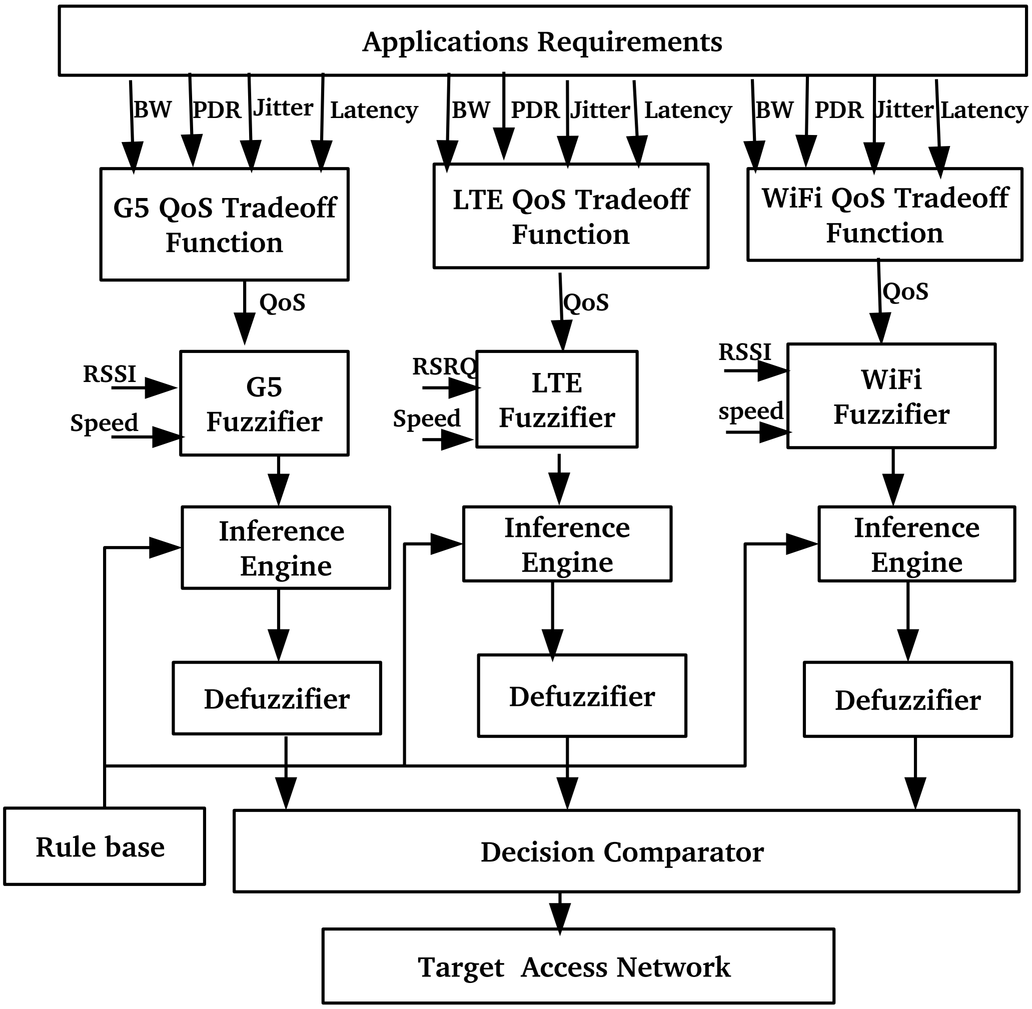


Figure 5.4 – Fuzzy logical model proposition

This makes our approach very specific, standards-compliant and close to the realistic situations. This design comes from our target of having a light and efficient system. In other words, we want to reduce the number of parameters used in the FIS because the rules increase exponentially with the number of used parameters and the fuzzy terms for each fuzzy linguistic variable (parameters). This is why we limit the number of parameters to 3.

To determine the parameters to use in the fuzzy system, we based our decision on making a cross-layer parameters design, considering the parameters' dynamicity and uncertainity, as it is one of the specific advantage of fuzzy logic. Therefore, the RSSI and speed were chosen as the most challenging and varying parameters, specifically in realtime applications in IoV fields. Then, we combined the rest of parameters in one varying parameters called expected QoS.

This QoS parameters also intend to express the variation in the predicted user quality of experience if a handover to the respective network was carried out.

We considered the speed as it is very important for VANETs scenario. After that, we compare the outputs (score value) of the FIS and select the one with the highest score value as the selected best candidate.

This will enhance therefore the perceived QoS by the user as we have already taken into account the applications' requirements. It might also avoid ping pong effects. Furthermore, our approach might be interesting in applying the flow mobility extensions and load balacing by rerouting every application to the network, which provides a good tradeoff with respect to this application. This is specially essential in the case of multihoming, where multiple networks are available at the same time.

5.4. Conclusion

In the following chapter, we are going to see how we have integrated the fuzzy logic in the NS3 and how we have implemented the proposed solutions. Simulation results will be also discussed.

Chapter 6

Implementation and simulation results

Until now, we have seen how VANETs and handover work in chapter 2 and chapter 3, we have applied them in our approach in chapter 4 and we proposed a fuzzy-based selection method in chapter 5. Now in this chapter 6, we will describe the implementations that we made to use them into the simulations and describe also their results. This chapter is presented as follows: section 6.1 will present the implementation steps that we have made, simulation results of PMIP-MIVH will be discussed in section 6.2 and the simulation using the proposed fuzzy algorithm (PMIP-FL) will be given in section 6.3.

6.1. NS3 implementations

6.1.1. Handover implementation in NS3

The only handover implementation that was available in NS3 was the horizontal handover in the LTE module. The LTE model description [1] and user guide for LTE implementation[2] in NS3 can be found on the NS3 website (https://www.nsnam.org) as open-source. However, all the LTE functionalities and specifications features were not available. Missed features have to be added on a per-user-specific needs basis.

To overcome this shortcomings, we will firstly specify the most important LTE features needed to understand the implementation of handover using LTE architecture, before describing the added features used in implementing our vertical handover approaches. Hence, in LTE implementation in NS3, there are two different ways of triggering the handover:

- Manually way (explicitly): This allows to schedule a handover trigger at specific time, by handing over a specific UE to a well known and specified eNB. This is achieved by triggering a Handover request method on the Radio Resource Control (RRC) entity of the source eNB.

[1] https://www.nsnam.org/docs/models/html/lte-design.html
[2] https://www.nsnam.org/docs/models/html/lte-user.html

- Automatic way: This is where a suitable handover algorithm is needed and used. Depending on the situations experienced by the UE, the source eNodeB will automatically trigger handover, according to conditions predefined in the applied handover algorithm.

In the automatic way, the process of the handover decision often passes through 4 steps which are: the measurements configuration, measurements performance checking, measurements report triggering, and finally the measurements reporting. Details can be found in appendix A.

6.1.2. Added implemented features in the LTE module for vertical handover support

In the classical implemented LTE module, there were many features that were not yet implemented in order to support vertical handover. Indeed, the present model was intended for horizontal handover in the E-UTRA access radio, which means that it only supports few features as reported in appendix A.1.

This means that:

- Event B1 and B2 that are very important for vertical handover were not implemented.
- Only X2-based handover (Intra-LTE handover) was implemented in LTE module
- For decision parameter, one criterion was considered: whether RSRQ (in A2A4RsrqHandoverAlgorithm), RSRP (in A3RsrpHandoverAlgorithm), distance between UE and cell in automatic attachment way, during the search selection step. Note that the RSRP and RSRQ are reported in term of range (0 -97 for RSRP and 0-34 for RSRQ) as specified in 3GPP TS 36.133 [136]. RSRP Measurement Report Mapping and RSRQ Measurement Report Mapping can be found respectively in section 9.1.4 and 9.1.7 of this standard [136]. The conversion from RSRP or RSRQ values to their respective range is implemented in LteCommon, using the following formulas:
  RSRP value to range:

$$Dbm2RsrpRange = Min(Max(floor(Rsrp + 141), 0), 97) \tag{6.1}$$

  Range to RSRP value :

$$RsrpRange2Dbm = range - 141 \tag{6.2}$$

RSRQ value to range:

$$Db2RsrqRange = Min(Max(floor(Rsrq * 2 + 40), 0), 34) \tag{6.3}$$

Range to RSRQ value :

$$RsrqRange2Db = (range - 40)/2 \tag{6.4}$$

This conversion in range and the range-decision-based also redirect us to the importance of using fuzzy logic for dealing with such values.

The procedure taken by A2A4RsrqHandoverAlgorithm is illustrated by the figure A.2. This algorithm is based on the A2 (serving cell's RSRQ becomes worse than threshold) and A4 (neighbour cell's RSRQ becomes better than threshold) measurements reports' Events. A2 event means that the UE is experiencing poor signal quality and may benefit from a handover. However, A4 is for detecting neighbouring cells and acquiring their corresponding RSRQ from every attached UE, which are then stored internally by the algorithm.

The A3RsrpHandoverAlgorithm is based on the RSRP and tends to hand the UE over to the strongest available cell in its neighbouring. We illustrate its procedure by the figure A.3. It is to be noticed that two variables: hysteresis and time-to-trigger, were introduced in order to mitigate the ping-pong effects that frequently affect that kind of handover algorithm.

For our approach, we replaced the one criterion (RSRQ or RSRP) by a corresponding metric ***"Score"*, which is a combination of many parameters**. Therefore, we are going to use the threshold as defined for B1 and B2 Events for vertical handover. Every time the vehicle receives measurements (i.e. periodically every 200ms), the fuzzy engine computes the score as a background application, finds the score of any connected network. Then it applies the A2A4RsrqHandoverAlgorithm syntax by replacing the RSRQ criteria by the overall *Score*. As we have defined the levels of network score, a minimun score under which the network might not be usable is also used. It corresponds to the low score. Thus, we defined this low score level as the ServingNetworkScoreThreshold. In the A2A4RsrqHandoverAlgorithm, we replaced the entering condition as:

$$ServingNetworkscore \leq ServingNetworkScoreThreshold \tag{6.5}$$

If the condition is true, then, our algorithm finds the best network candidate with respect to the respective score, which were previously computed by the engine. To avoid ping-pong effects, we also define a scoreOffset between the

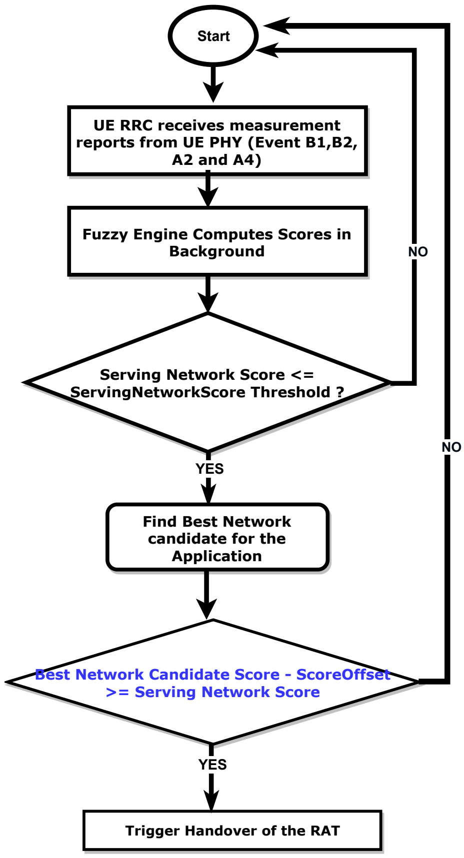


Figure 6.1 – Procedure for our proposed Fuzzy multiple criteria-based vertical handover algorithm (PMIP-FL)

serving network score and the best network candidate, that must be met in order to trigger the handover. Our algorithm is illustrated by the figure 6.1

For vertical handover, we therefore implemented some important features that we detailed in appendix A.2.

6.1.3. Integration of Fuzzy Logic in NS3

As discussed in [185], fuzzy systems are actually widely used in different applications in a lot of industrial and research projects. Therefore, many fuzzy system software and libraries have been developped and are commercially available or open-source. However, no integration of fuzzy logic was available in the NS3 simulator. For that, we have decided to integrate the fuzzylite [186] library in NS3 in order to perform our simulations. Fuzzylite is a free and open-source fuzzy logic control library programmed in C++ for multiple platforms (e.g., Windows, Linux, Mac, iOS). It is also implemented in other programming language such as Java and Android as jfuzzylite. A Qt version is commercially available. To do this integration, we firstly compiled and installed the fuzzylite library. Then, we included the fuzzylite path and its dependencies in our project. This integration process is detailed in appendix A.2.1.

Therefore, we can use the fuzzy library in our project by inserting

```
#include <fl/Headers.h>
```

However, for the program files located in some directories of NS3 (such as the scratch directory), a workaround was needed in order to handle them, as detailed in appendix A.2.1.

6.1.4. Integration of Fuzzy Logic in the PMIP-MIVH

The vertical handover execution is done using the distributed PMIP functions. Thus, in the PMIP-MIVH algorithm, we introduced the fuzzy logic in the part of monitoring disconnection as illustrated by figure 6.2. Since the measurement are reported every 200 ms by default, we use the fuzzy engine to compute the fuzzy logic and compare the most convenient interface on which it is better to receive packets. Therefore, the algorithm checks both the signal quality, the QoS metric and the estimated UE speed in order to anticipate the RAT switching instead of waiting that the interface goes down. Thus, this aims at reducing again the probability of losing packets.

6.2. PMIP-MIVH implementation and results

To test and validate our proposal of vertical handover that we named PMIP-based Mobile Internal Vertical Handover (PMIP-MIVH), we have performed simulation using 3 interfaces per vehicle: one for ITS G5 called WAVE, one for LTE and another one for WIFI. We followed the PMIPv6 implementation as described in [187]. Then, we modified and extended some components from this specification, especially the Ipv6L3Protocol. Concerning the LTE implementation, we have followed the specification of supporting PMIPv6 standard in LTE [132, 147] as we have described it in section 3.1.2. Thus, as we are in the context of vertical handover, the S1 interface (between the eNB and SGW) and S5/S8 interface (between SGW and PGW) were used. Note also that the X2 interface (between eNBs) is still available, but it is used for horizontal handover (intra-LTE and inter-LTE Handovers). Thereafter, we implemented the logical interface feature which is presented by the algorithm 1. We use one logical interface (a VirtualNetDevice instance)

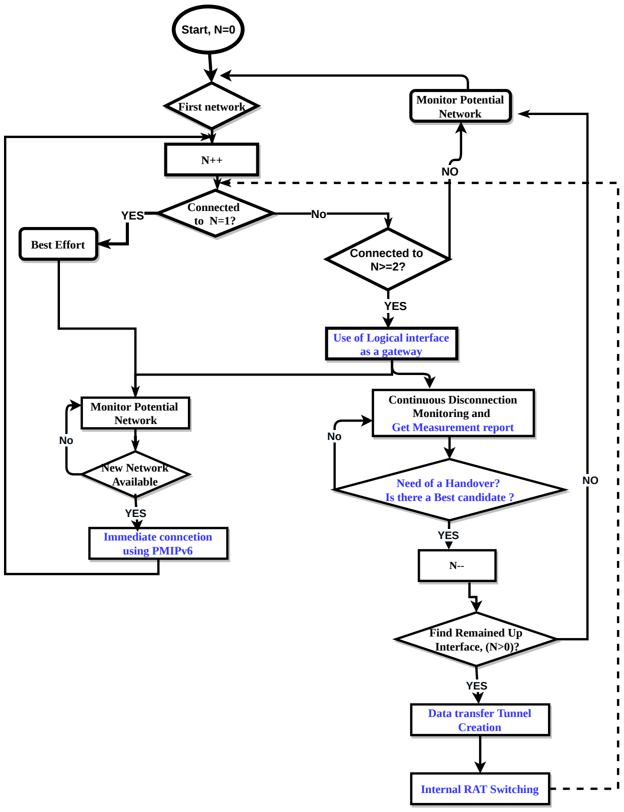


Figure 6.2 – Mobile Internal Vertical Handover (MIVH) using Fuzzy Logic in the decision phase

per vehicle, which will be the only interface visible to the outside of a vehicle, to serve as a gateway for other available interfaces (physical network devices). To the point of view of upper layers and CNs, these latter interfaces are therefore seen as virtual devices installed inside the vehicle, while the logical interface becomes shown as the physical device of the mobile. However, this logical interface has an exception: it could not be turned down (Radio Agnostic as proned by PMIPv6) to the CNs and upper layer's point of view. Thus, it allows the transparent handover execution and the session continuity maintenance.

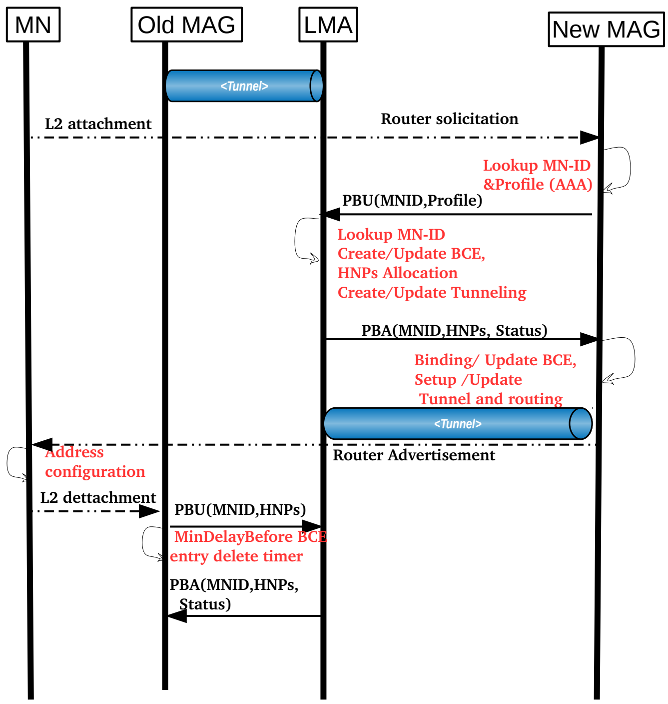
The functionnalities of the algorithm has been already explained in section 4.1. We designed and implemented the scenario illustrated by the figure 4.4 in NS3.

It is to be noticed that the PMIPv6-based approach functions can be grouped into five categories, which are:

- Mobile Node attachment detection

- Binding update operation and registration
- Tunneling and routing
- MN address configuration
- MN detachment

The figure 6.3 illustrates the sequence diagram of the PMIPv6 control plane which is mainly composed by those functions. This figure also highlights the interaction of PMIPv6 main entities in order to execute those main functions.



(a)

Figure 6.3 – Sequence diagram of PMIPv6 main functions for the control plane

We have therefore measured and checked if all these PMIPv6 major functions and requirements are present and well functioning. For more details on the connexion establishment and implementation validation, see appendix B.

6.2.1. Definition and description of the performance metrics

For handover performance measurement, we consider 2 unicast real-time applications using UDP between the UE and the CN (application of remote monitoring and trajectory correction of a self-driving car). In the first application, CN is the sender and UE is the receiver (remote driving command informations), whereas the UE is the sender and CN is the receiver in the second application (collection of vehicles data from vehicle's sensors). This allows us to test the real-time application metrics. The definition and description of the measured performance metrics are given below:

- End-to-End delay: It represents the time that a packet takes to travel from the sender node to the receiver node. It is calculated as the difference between the reception timestamp at the receiver and the transmission timestamp at the sender.

$$\text{Delay} = \text{Reception time -Transmission time} \tag{6.6}$$

- Jitter: It represents the variation between the packets' delay. It is defined as the difference time in the packet inter-arrival time. In other words, the jitter is a delay that causes some packets to arrive later than the expected arrival time at the destination. It is calculated by monitoring the variation of the difference time between the reception time for the current packet and the reception time of the previous packet at the receiver node side.

- Packet Delivery Ratio (PDR): it represents the reception ratio. It is calculated as the ratio of the total received unicast packets divided by the total sent unicast packets.

$$\text{PDR} = \frac{\text{Total received packets}}{\text{Total sent packets}} \tag{6.7}$$

- Packet Error Rate (PER): it reperesents the packet loss ratio. It gives an idea about the total number of lost packets compared to the total number of sent packets.

- Throughput: It represents the datarate at which packets were sent on the available bandwidth of the channel. It is calculated by measuring the number (multiplied by the size) of received packet per unit of time (seconds).

$$\text{Throughput} = \frac{\text{Total received packets} \times \text{Packet size}}{\text{Duration}} \quad (6.8)$$

where ***duration*** represents the time during which the considered ***total Received Packets*** number were sent from the transmitter and received at the receiver.

For mobility topology, we considered a two-lane highway as illustrated by figure 6.4, vehicles are moving in the same direction, with 20m as inter-vehicle distance. The used mobility model is "Constant Velocity Mobility Model". Regarding the wifi channel, we maintained the default model, which means that we create a channel model with a propagation delay equal to a constant *the speed of light*, and a propagation loss based on a *log distance model* with a reference loss of 46.6777 dB at reference distance of 1m. Figure 6.4 represents a NetAnim[3] screenshot, illustrating the simulation scenario, and default parameters that we used in the simulation are given in the table 6.1.

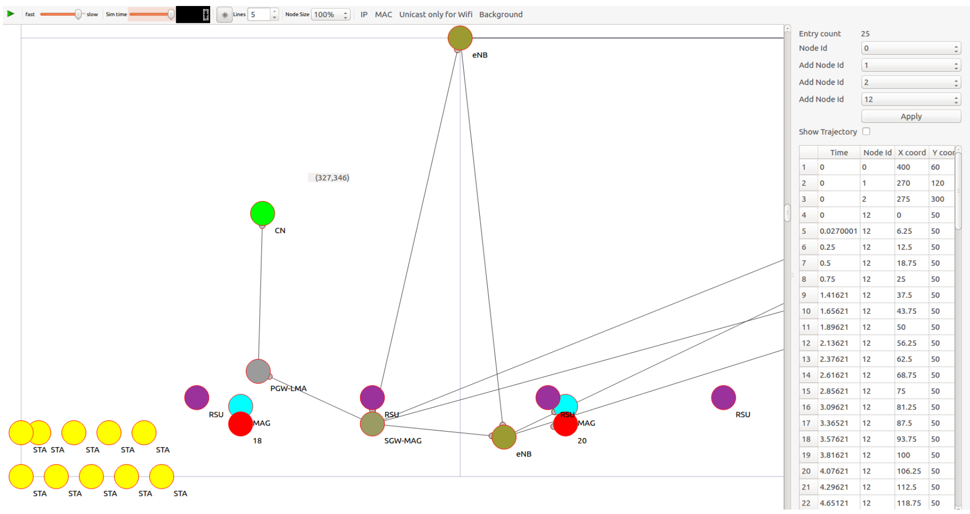


Figure 6.4 – Example of simulation scenario

We have then varied the number of host per MAG in order to evaluate the impact of the binding and lookup time at the PMIPv6 entity (MAGs and LMA), then we varied the hop count between MAGs. Finally, we varied

[3]An offline animator based on the Qt toolkit, which animates the simulation using an XML trace file collected during simulation. https://www.nsnam.org/wiki/NetAnim_3.108

the packet size in order to consider applications which might use high data volume in communications such as VoIP and real-time applications, as it might happen in self-driving cars.

Table 6.1 – Default parameters values used for the PMIP-MIVH performance simulation

Parameters	Default value
$N_{Host/MAG}$	2
N_{MAG}	20
H_{MN-MAG} H_{CN-MAG}	1
Packet size (bytes)	1024
Speed (m/s)	20
α	3
β	1
τ	1
κ	4
first MAG position	(250,80,0)
first AP position	(250,60,0)
second MAG position	(620,80,0)
second AP position	(620,60,0)
PGW (LMA) position	(270,120,0)
SGW position	(400,60,0)
CN position	(275,300,0)
first RSU position	(200,90,0)
UE start position	(0,0,0)
eNB DL EARFCN	100 MHz
eNB UL EARFCN	18100 MHz
eNB DL bandwidth	25 RBs
eNB UL bandwidth	25 RBs
eNB TxPower	46 dBm
Mobility Model	ConstantVelocity
inter-Vehicle distance	20 m
number of road line	2
Wifi PHY model	YansWifiPhy
Wifi MAC model	NqosWifiMac
WAVE MAC model	NqosWaveMac with OcbWifiMac
Propagation delay Model	ConstantSpeed-PropagationDe-layModel
Propagation Loss model	LogDistance-PropagationLoss-Model

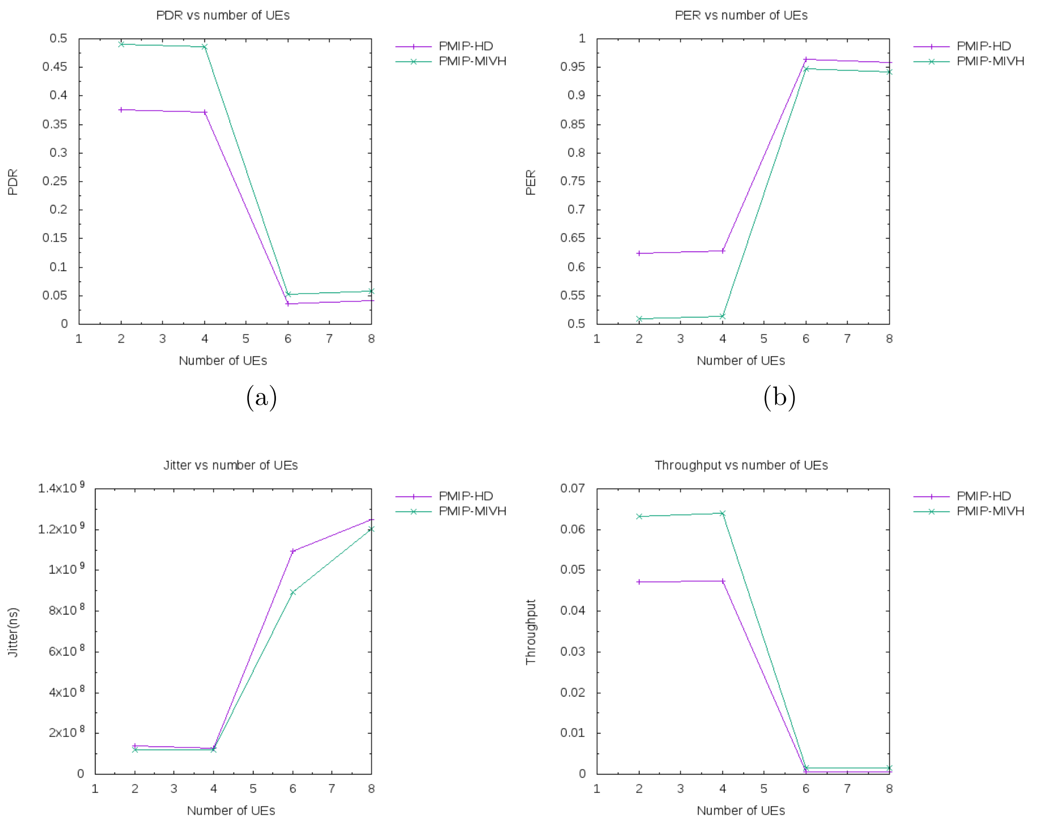
The simulation results are given and discussed in section 6.3.2.

6.2.2. Comparison and Discussion of simulation results

In the following simulation results and discussion, we will consider the DMM solutions by comparing our proposed PMIP-MIVH solution with PMIP-HD for the reasons already explained in the section 4.4.

6.2.2.1. Number of vehicles (UEs) impact

Through figure 6.5, we aim to verify the impact of lookup time by increasing the number of UEs that are present in the simulation, and consequently, which might increase the BC table size. For both solutions (PMIP-HD and our solution PMIP-MIVH), when measuring the PDR (figure 6.5a) and consequently the PER (figure 6.5b), we notice that the PDR decreases as the



(a) (b) (c) (d)

Figure 6.5 – Number of vehicles (UEs) impact: (a) PDR (b) PER (c) Jitter (d) Throughput

number of UEs increases. Consequently, the PER increases as the UEs number increases. This variation is also remarked for the throughput (figure 6.5d) which decreases as the UEs number increases. The jitter, illustrated by figure 6.5c, increases according to the increasing of the number of UEs. This proves that the lookup has an impact on the vertical handover process. However, in all of these measured performance metrics, our approach shows an improvement. Indeed, until the average number of UEs (4 UEs at these figures), our PMIP-MIVH presents high PDR and high throughput values compared to the PMIP-HD values. PMIP-MIVH has also lower PER and jitter. Even though, this values degrades very rapidly when the number of UEs increases. These results highly depends on the number of resources that are available at the MAGs and eNBs (section 7.1.6 in [188]) and consequently, how these resources are managed. Notice that the ressource management

[189, 190] is very complex and very different from Wifi networks to LTE networks. A thorough review on resource management is given in [191, 189]. Thus, it is to be noticed here that the ressource management is outside of this thesis scope.

6.2.2.2. Impact of distance between MAGs

In order to see the impact of the number of MAGs in the PMIP domain, which may influence the distance between two MAGs (distance between the MN's MAG and the CN's MAG), we used the hop count between the MAGs and measure the PDR, PER, jitter, delay and throughput. In figure 6.6a, illustrating the PDR, our PMIP-MIVH shows a difference of about (0.488166-0.360947= 0.127219) compared to PMIP-HD when the hop count is 40. This represents around 26% of improvement. This result is also remarkable for the PER in figure 6.6b. These results show that our approach highly benefits from the use of logical interface in order to increase the packets reception. In fact, by rerouting the received packet to the remained connected physical devices, the logical interface reduces the number of packets that might be lost in PMIP-HD by triggering the handover when an interface failed to correctly receive the packets due to a weak network coverage.

Concerning the jitter, figure 6.6c shows that our approach is still performing well, because it has for example (121.436-116.921= 4.515) ms less than PMIP-HD when the hop count between MAGs ($hMAGMAG$) is equal to 60. This represents around 3.71% of improvement in jitter in average. This also depends on the number of packets that are not correctly received or completely lost, which increases the jitter. An increase in the number of lost packets implies higher jitter.

The throughput improvement is illustrated by figure 6.6e. It can be seen that our method also improves the throughput average of around (0.0624176-0.0467316 = 0.015686) MBits/sec. This represents on average 25.13% of improvement. This is also due to the reduction of the number of lost packets thanks to the use of the logical interface in our approach.

The average delay measures (figure 6.6d) do not show any great difference between the two approaches. However, this proves that our approach can improve the PDR and the throughput without degrading the delay performances. Which is also very important, especially for non fault-tolerant applications.

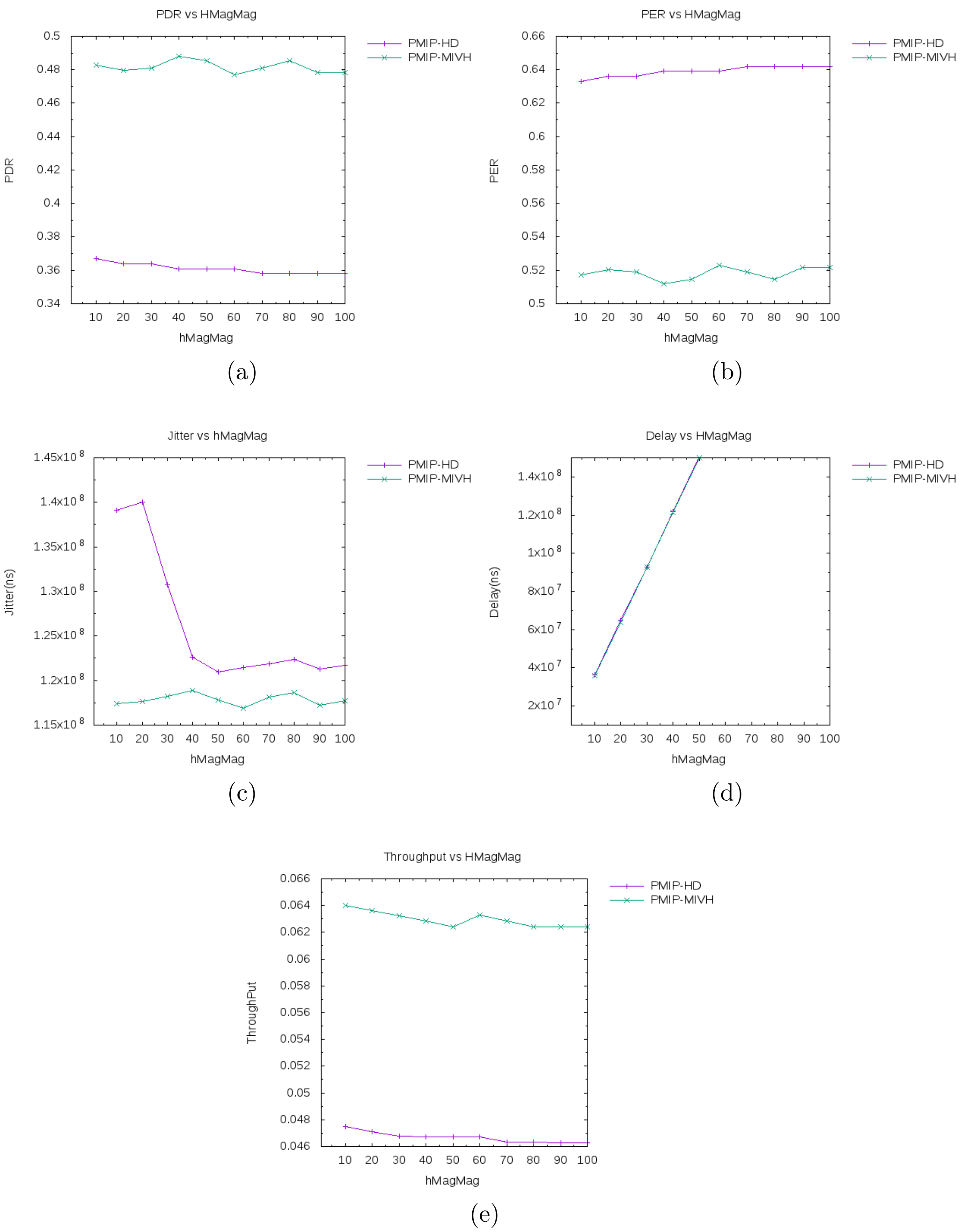


Figure 6.6 – Impact of distance between MAGs: (a) PDR (b) PER (c) Jitter (d) Delay (e) Throughput

6.2.2.3. Impact of packet size

In order to see what happens if we have a high volume data or big size packets, we varied the packet size and measured the behavior of the two

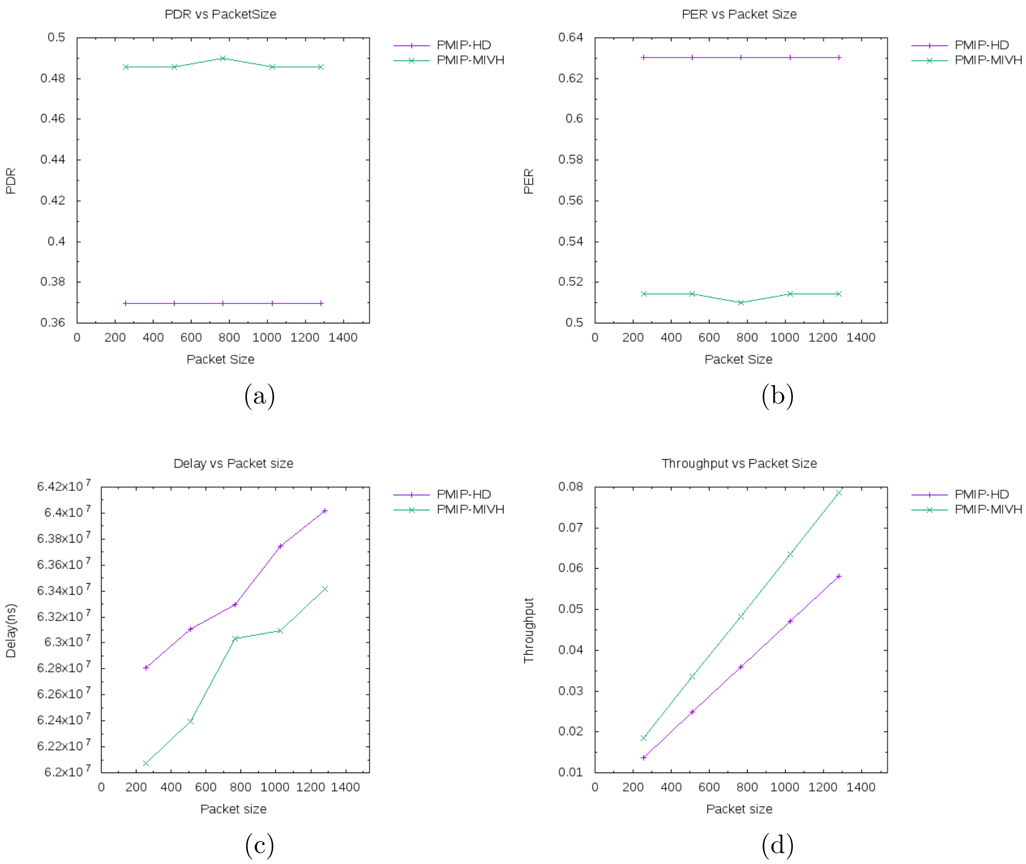


Figure 6.7 – Impact of packet size: (a) PDR (b) PER (c) Delay (d) Throughput

solutions. The results are illustrated by figure 6.7. On the figure 6.7a and figure 6.7b, illustrating respectively the PDR and the PER, we see that until a certain packet size (1024 in our simulations), the PDR and respectively the PER do not change greatly. This means that both of the two solutions can support applications while varying different packet sizes (from 256 to 1024 bytes in our simulations). Furthermore, we can see that our PMIP-MIVH has better performance in both PDR and PER compared to the PMIP-HD. Concerning the packet average delay, illustrated by figure 6.7c, we can see that the delay increases with the packet size. In fact, the average delay which is about 62.0189 ms with a packet size of 256 bytes in PMIP-MIVH becomes 63.4334 ms when the packet size passes to 1024 bytes. Likewise, the packet average delay which was about 62.8293 ms with a packet size of 256 bytes with PMIP-HD, becomes 64.1806 ms when the packet size becomes equal to 1024 bytes.

Meanwhile, our approach's values are always lower than those of PMIP-HD and presents an improvement of over 1.16% when using packets of 1024 bytes.

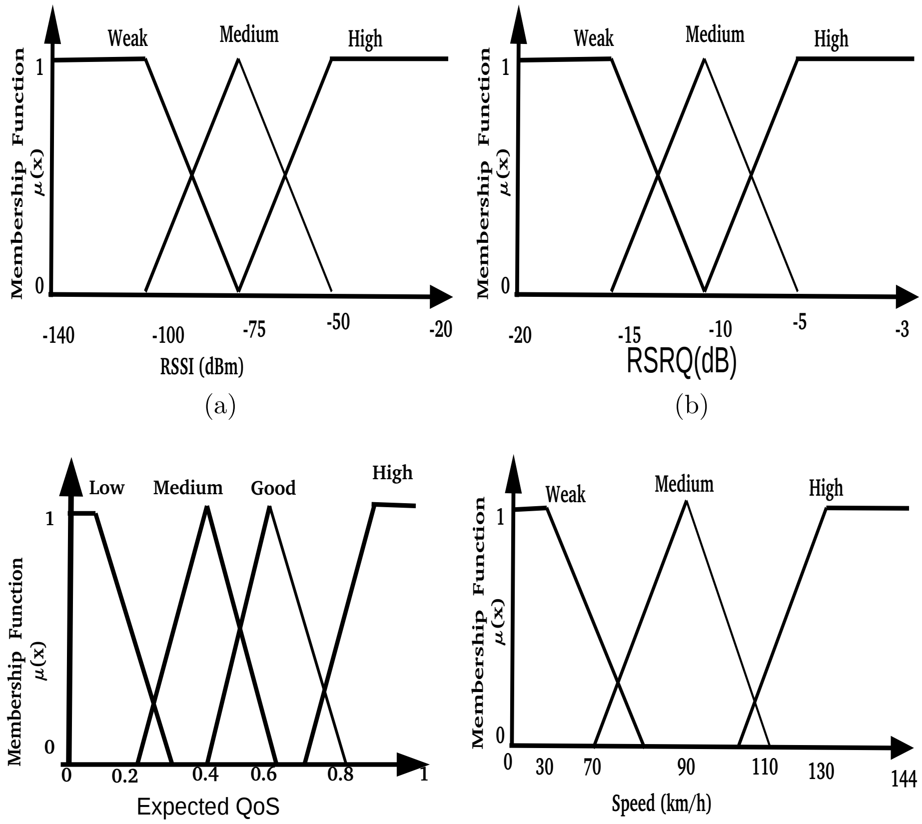
Concerning the throughput, figure 6.7d shows that the throughput increases proportionally to the packet size. Which is an obvious and expected result, since it is calculated considering the packet size of the received packet during a sample interval period. Furthermore, we can notice that our approach have higher throughput values than the PMIP-HD solution. This is also due to the increase in the number of received packets in our approach compared to the PMIP-HD approach, which is also proved by the PDR.

6.3. Implementation and results of the Fuzzy Logic-based algorithm

6.3.1. Construction of the Knowledge database

The first step in the fuzzy logic system is the fuzzification. For this step, linguistic variables and Membership functions must be first designed. For each parameter, we have considered the following fuzzy terms and their corresponding membership functions as illustrated by figure 6.8.

As illustrated by this figure 6.8, for the sake of simplicity, we have used two type of membership functions: Ramp and Triangle. The Ramp membership



(a) (b) (c) (d)

Figure 6.8 – Fuzzy terms and Membership function representation: (a) RSSI (b) RSRQ (c) Expected QoS (d) Speed

function (x) is mathematically expressed as :

$$\mu(x) = \begin{cases} 0h, & \text{if } x = e \\ \begin{cases} 0h, & \text{if } x \leq s \\ 1h, & \text{if } x \geq e, \text{ if } s \leq e \\ h(x-s)/(e-s), & \text{otherwise} \end{cases} \\ \begin{cases} 0h, & \text{if } x \leq s \\ 1h, & \text{if } x \leq e, \text{ if } s \geq e \\ h(s-x)/(s-e), & \text{otherwise} \end{cases} \end{cases}$$

where h is the height of the ramp, s is the start of the ramp, and e is the end of the ramp. whereas, the triangular membership function is mathematically expressed as:

$$\mu(x) = \begin{cases} 0h, & \text{if } x \notin [a, c] \\ 1h, & \text{if } x = b \\ h(x-a)/(b-a), & \text{if } x \leq b \\ h(c-x)/(c-b), & \text{otherwise} \end{cases}$$

where h is the height of the triangle, a is the first vertex, b is the second vertex , and c is the third vertex of the triangle. The score membership is also given in the figure 6.9.

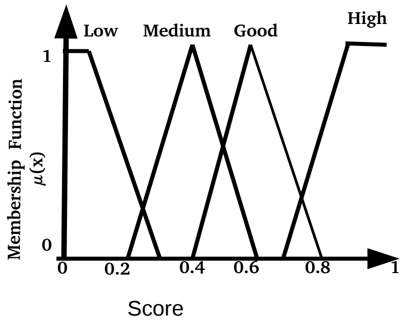


Figure 6.9 – Score Membership function representation

By considering the advantages and characteristics of each of the available RATs taken into account (ITS-G5, LTE, WiFi), we have constructed the rules knowledge database as follows:
For ITS-G5 score:

- if RSSI is high and QoS is high then Score is high
- if RSSI is high and QoS is good: two possibility: if speed is low (LTE can support the latency) then score is good, otherwise score is high (for medium and high speed)
- if RSSI is high and QoS is medium: two possibility: if speed is high then score is good, otherwise score is medium (for low and medium speed)
- if RSSI is high and QoS is low: then the score is low. This is where, our approach "highly" differs from RSS-based approach. In contrast to traditional and RSS-based approach, which might still privilege this network with high RSS, but with no QoS, our aproach must try to maximize both the RSS and the QoS. Then, when these two parameters

are satisfied, our approach prioritize the ITS-G5 for high speed. If we have high speed, safety applications must be run on the ITS-G5.

- When the RSSI is medium, the communication might be possible if the QoS is high or good. Therefore the score is good
- If RSSI is medium and QoS is medium the score is medium, we will see if we can anticipate the handover, if there is a better candidate. Otherwise, we stay using this current network. However,
- if we have a medium RSSI with a low QoS, the score is automatically low because the applications' requirements must not be respected. This is also another difference with the traditional approaches.
- When RSSI is weak, the score is automatically low. Because, even if the QoS may be good or high, it will only last few time. This is due to the fact that, without a medium signal, there will be loss of packets. Subsequently, the PDR will directly drop, the jitter and latency will directly increase. Therefore, the QoS will degrade subsequently. Reason why, we have to anticipate and prepare a handover to another available network.

For LTE and Wifi networks, the proccess is similar, except that when the speed is high, the Wifi and LTE are penalyzed and the ITS-G5 is privileged in the previous description. Another thing is that for LTE, the RSSI is replaced by RSRQ. Therefore for LTE score, :

- if RSRQ is high and QoS is good: the score is good. No possibility of score high as it was in ITS-G5.
- if RSRQ is high and QoS is medium: the score is medium. Depending on the problem and complex ressource management on LTE, when the resource are not guaranted, a medium QoS may degrade the performance. That is, it may decrease the bandwidth, the PDR and therefore increase the jitter and latency. Therefore, the score is medium

Finally, for wifi score :

- if RSSI is high and QoS is good: the score is good. No possibility of score high as it was in ITS-G5.
- if RSSI is high and QoS is medium: the score is medium. Depending on the CSMA/CA mechanism in standard wifi, a medium QoS may degrade the performance. That is, it may decrease the availability

of the channel (channel busy). Therefore, it may decrease the PDR and therefore increase the Jitter and latency. Therefore, the score is medium.

This gives us 3*3*4 (QoS has 4 terms) = 36 rules per network block. Therefore, thanks to the fuzzy logic, we have in total 108 possible scenarios, which might be difficult to handle with traditional mathematical approaches, which is not the case for the fuzzy logic.

6.3.2. Comparison and discussion of simulation results

As what was done for testing the PMIP-MIVH solution, we have made other simulations in order to evaluate the performance of our proposed fuzzy logic-based algorithm (PMIP-FL). For that, we have implemented the following 3 solutions:

- RSS-Based algorithm, which represents the traditional vertical handover algorithms that are based on the strength of the received signal (RSSI or RSRQ),
- PMIP-MIVH which is our previous proposed vertical handover approach
- PMIP-FL which implements our fuzzy logic-based algorithm, and which extends our PMIP-MIVH approach.

In addition, in order to evaluate the precision of our simulation results, we have calculated the confidence interval using the following formula:

$$Confidence\ Interval = X \pm Z_{\alpha/2} \times \frac{\sigma}{\sqrt{(n)}} \tag{6.9}$$

Where X is the mean, α is the confidence level (95% in our case), σ is the standard deviation, n is the number of simulations and $Z_{\alpha/2}$ represents the confidence coefficient[4]. Thus, the computed $Z_{\alpha/2} \times \frac{\sigma}{\sqrt{(n)}}$ value represents the margin of error for each mean value. We used the same parameters as those of table 6.1 but we modified the following parameters reported in table 6.2.

We provide the comparison results and discussion in the following sections. The overall PDR, jitter, delay, PER and throughput have been computed.

Table 6.2 – Default parameters values used for the performance evaluation of the fuzzy-based algorithm.

Parameters	Default value
$N_{Host/MAG}$	10
Speed (m/s)	25
eNB DL bandwidth	100 RBs
eNB UL bandwidth	100 RBs
Vehicles number	5-40

6.3.2.1. Number of vehicles (UEs) impact

In order to verify the impact of lookup time and the vehicle number on the performance of our proposed fuzzy logic-based algorithm, we have plotted in the figure 6.10, the performance metrics results obtained by increasing the number of UEs (vehicles) that are present in the simulation. The PDR result illustrated by the figure 6.10a and consequently the PER result illustrated by figure 6.10b both show that our PMIP-FL algorithm is better that the RSS-Based and PMIP-MIVH approach. This proves that the usage of fuzzy logic method might be a good way of handling values in handover algorithm. However, through the computed confidence interval which shows the variation of the mean, we can see that in all those solutions, the PDR smoothly decreases while the PER smoothly increases when the number of UEs present in the simulation increases. This smoothness is benefited from the distributed approach of PMIPv6, which might help in the scalability of our solutions. The throughput's plot in figure 6.10e also follows the same variation direction by smoothly decreasing when the UEs number increases. Nevertheless, when looking for the jitter result in figure 6.10c, we see that our proposed FL-based method (PMIP-FL) also presents an improvement in terms of the jitter. This figure also illustrates that this jitter smoothly increases when the UEs number increases.

Furthermore, the delay result illustrated by the figure 6.10d does not show any noticeable difference in term of improvement. However, the confidence interval also shows that the mean variation for our PMIP-FL algorithm is often lower, compared to the other solutions. This could mean that our PMIP-FL was able to improve the handover performances while maintaining an acceptable delay. All these results assumed that they are enough resources allocated in the access points (APs and eNBs in LTE) in order to maintain an acceptable service. Reason why, in addition to the RSS indicator, we have included the expected QoS metric in our decision system (PMIP-FL algorithm) in order to always be aware about the availability of the required

[4] https://www.wikihow.com/Calculate-Confidence-Interval

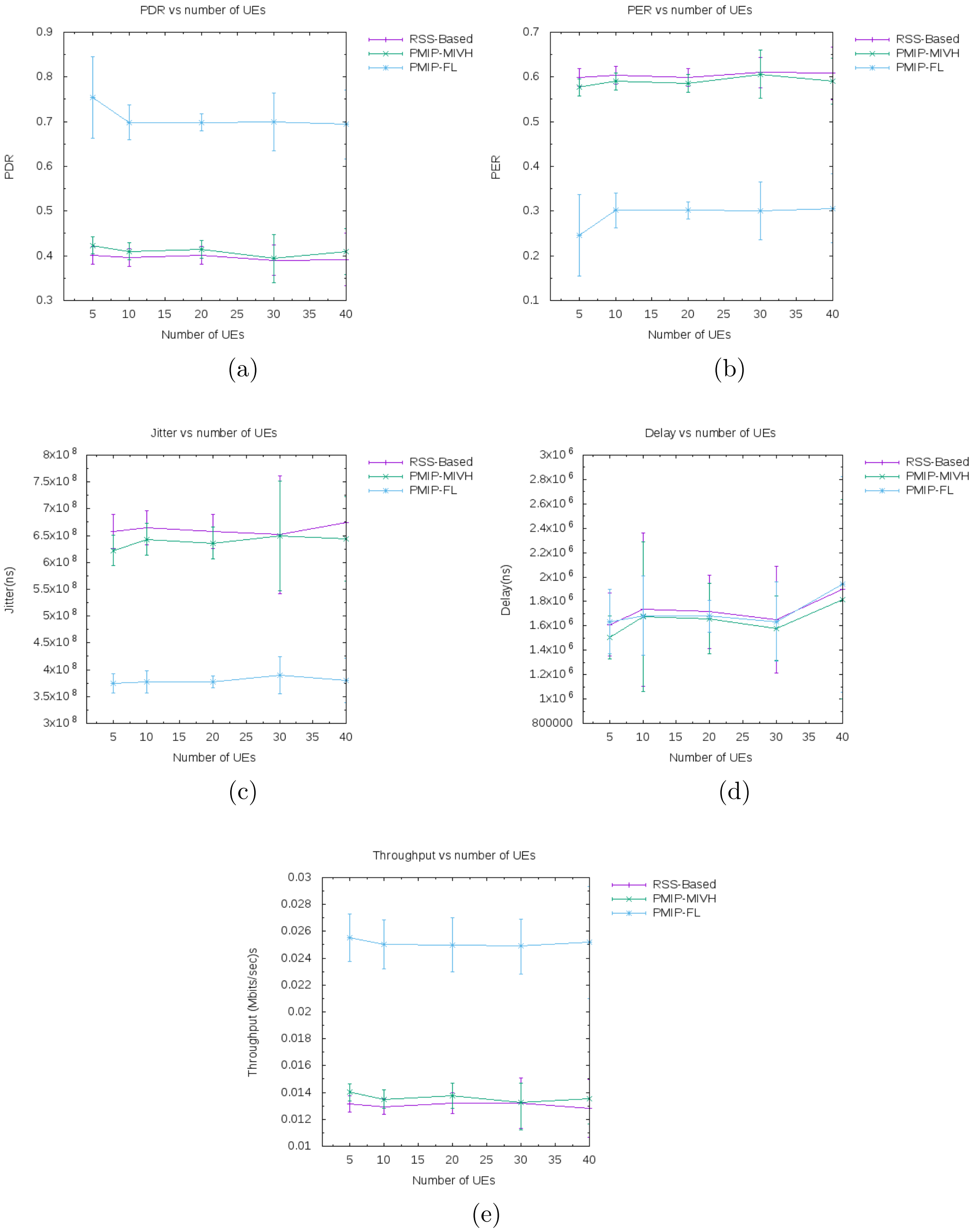


Figure 6.10 – Number of UEs impact: (a) PDR (b) PER (c) Jitter (d) Delay (e) Throughput

resource for an application before handing the vehicle over to a candidate network.

6.3.2.2. Impact of distance between MAGs

When using PMIP solution, the MAGs entities are of great importance since they are responsible for UE signaling and UE connectivity detection. Therefore, the number of available MAGs in the PMIP domain somehow influences on the resource management, thus influencing the performance of the handover algorithm. This number also dictates the position of the MAGs and the distance between two MAGs (distance between the MN's MAG and the CN's MAG).

By using the hop count between these MAGs, we measured the impact of the number of MAGs by measuring and plotting the PDR, PER, jitter, delay and throughput.

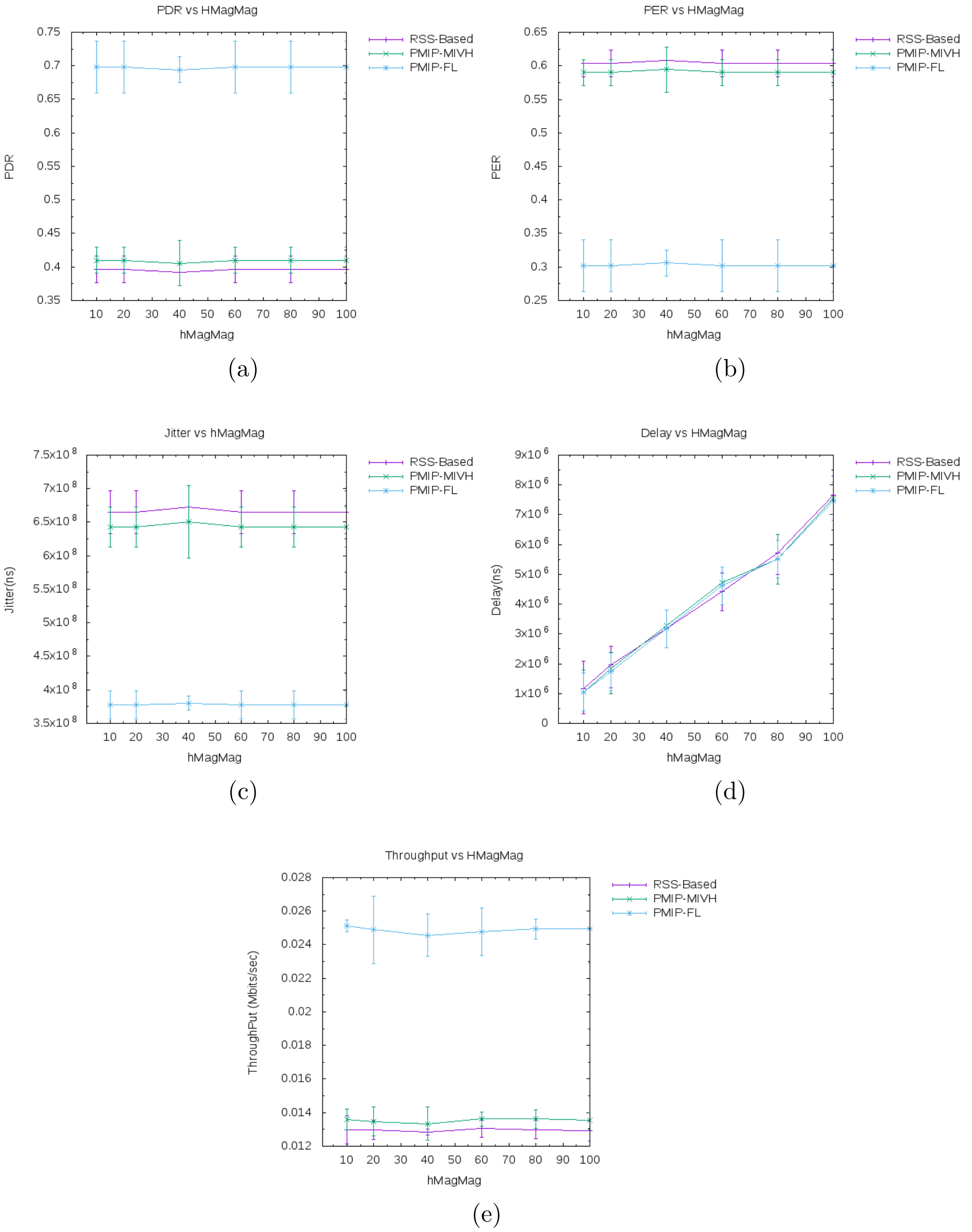
Here also in figure 6.11, the Proposed PMIP-FL method overperforms the RSS-Based and PMIP-MIVH solutions by having a higher PDR, higher throughput, while presenting lower jitter and lower PER.

Thus, for the PDR illustrated by figure 6.11a, it is shown that the fuzzy logic based method often presents a great difference compared to the other solutions. The average difference is about (0.698198-0.409909667 = 0.288288333) compared to PMIP-MIVH when the hop count is 100. It goes over (0.698198-0.396396333= 0.301801667) when compared to the RSS-based PDR values at the same point. This represents around 41.2% of improvement over PMIP-MIVH and up to 43.3% of improvement over the RSS-Based solutions.

The repercussion of this improvement is therefore made in the PER result in figure 6.11b. These results demonstrate that the proposed fuzzy logic based selection method is able to make the tradeoff between RSS and QoS parameters in order to improve the packet reception, and consequently the performance of the handover algorithm. In fact, our algorithm anticipate the handover when the QoS parameters degrades even though the RSSI might still be acceptable. This is also a great difference with the PMIP-MIVH approach which made the interface switching when it detects that an interface is no longer up.

Losing packet might have great impact on the jitter. This is what the jitter plotted in figure 6.11c confirms by highlighting the improvement of our proposed handover algorithm PMIP-FL in term of jitter. Noticeably, the computed jitter of PMIP-FL is always around 377.5ms, while it reaches 645 ms in PMIP-MIVH and even 665 ms in RSS-Based when the distance reaches 100 hop counts.

Thus, by using the PMIP-FL selection method, we can expect to reach an improvement of 43.5% and 41% compared to those of RSS-Based and PMIP-MIVH, respectively when the distance between the MN's MAG and the CN's MAG is above 80 hop counts.



(a) (b) (c) (d) (e)

Figure 6.11 – Impact of distance between MAGs: (a) PDR (b) PER (c) Jitter (d) Delay (e) Throughput

The throughput improvement is illustrated by figure 6.11e and consolidates the same results. We can see an improvement similarity to those of the PDR plot in figure 6.11a, since the PMIP-FL throughput are always higher than those of the other considered solutions. To show this, the PMIP-FL method improves the throughput around 0.011735034 MBits/sec and around 0.011171467 MBits/sec in average, compared to RSS-based solution and PMIP-MIVH respectively. Which respectively represents 47.34% and 45.07% of performance improvement. This is also due to selection of the right network which maximizes the RSS quality and the computed Expected QoS metric value.

It is also to be noticed through the figure 6.11d that all these fuzzy logic based improvements do not have a noticeable impact in terms of delay. Indeed, the average delay measures show that the proposed solutions still maintain a somehow similar delays. However, it is to be noticed that this delay increases proportionally to the increase of the hop counts between the CN's MAG and the MN's MAG. Thus, a good distribution of MAGs' position is of great importance in order to maintain acceptable service. Furthermore, delay improvements may also be possible on an application-based basis.

6.3.2.3. Impact of packet size

By figure 6.12, we wanted to see what happens if we have a high volume data or big packets. The result in terms of PDR, illustrated by figure 6.12a, and the PER, illustrated by figure 6.12b, show that the mean values of PDR smoothly decreases, while the mean values of PER smoothly increases when the packet size increases. However, when looking to the confidence interval, these results do not show any great impact of packet size under 1024 KB for all these considered solutions. Thus, we can conclude that these solutions can support applications while increasing the packet size. We can notice also that the fuzzy logic-based solution (PMIP-FL) maintains its performances better than the two other solutions. These results remain true also for jitter metric as illustrated by figure 6.12c.

However, the packet size influences the throughput as well as the delay, as it is shown by the figure 6.12e and figure 6.12d, respectively. Indeed, these figures indicate that the throughput as well as the packet delay increase proportionally to the packet size. However, it is to be noticed that, in terms of delay, these results, again, do not show great difference between these solutions.

Furthermore, we can also notice that the fuzzy logic-based solution (PMIP-FL) remains with higher throughput values than the RSS-based and PMPIP-MIVH solutions. This is also due to the increase in the number of received packets in this fuzzy logic-based selection method than in the other solutions.

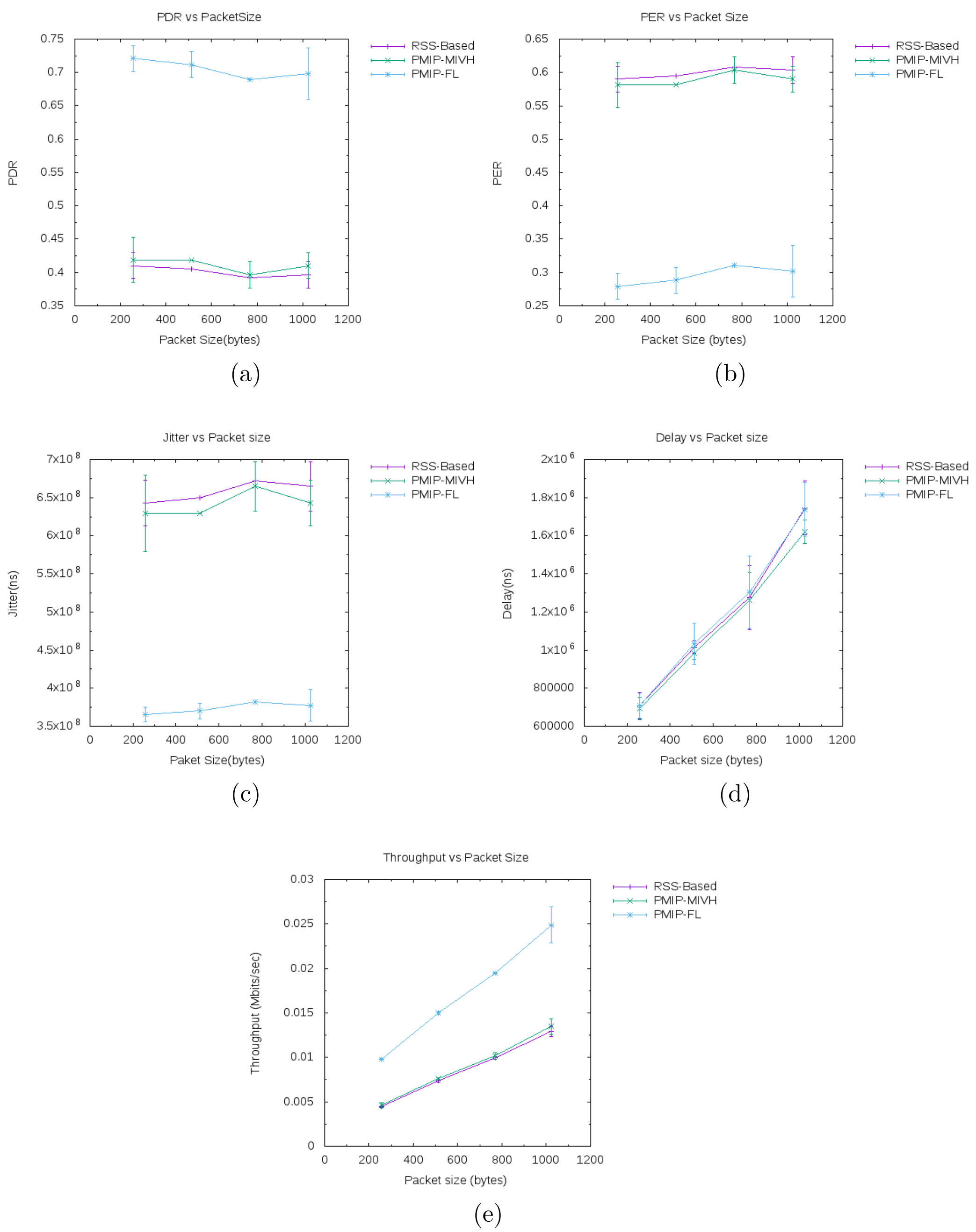


Figure 6.12 – Impact of packet size: (a) PDR (b) PER (c) Jitter (d) Delay (e) Throughput

Chapter 7

Conclusions and Perspectives

7.1. Conclusions

Connected and autonomous vehicles' deployment enables new ways of transportation and many new business markets are already created in this field. However, self-driving cars are very challenging and need efficient coordination of many tasks and operations that will enable vehicles to make their own decisions, without human intervention.

Through chapter 2, we have proposed an overview of advancements that recently took place in IoV domain. we highlighted the vehicles' communication and continuous connectivity issues. Then, we proposed a review of the mechanisms that need to be performed in order to achieve seamless handovers between available networks, therefore allowing vehicles to move from one network to another while maintaining session continuity (i.e. without losing connectivity and communication capabilities).

Firstly, a review of recently proposed IoV deployment architectures and D2D communications was made in this chapter. The main aim and contribution of this part were to demonstrate why crosslayer-based handover mechanisms are very essential in the IoV domain and autonomous cars' deployment. In section 2.5, we proposed our own classification of existing handover mechanisms in cellular and vehicular networks. We defined the classification criteria such as RAT technologies, handover execution manner, handover decision actor, the number of involved layers (levels) during the handover, the type of architecture used to execute the handover and the event that triggers the handover initiation. Thus, based on these criteria, we proposed a recent and complete classification by including and highlighting the distributed mobility management (DMM) approaches which are recent in the literature and still present ongoing activities of standardization.

In chapter 3, we performed a study on handover protocols in the LTE technologies. We have presented a case of study of the mobility management in LTE that illustrates the PMIPv6 implementation in section 3.1.2. The LTE standard enhancements for V2X services support have also been described in section 3.2.

In section 3.3, we have seen how the decision phase is very complex and needs to be well designed in order to have a reliable and efficient vertical handover. We have proposed an overview of the most popular MADM methods and we highlighted the advantages of the AHP method and Fuzzy Logic theory.

Then, in chapter 4, we have proposed our vertical handover mechanism denoted Proxy MIPv6-based Mobile Internal Vertical Handover (PMIP-MIVH), that uses a logical interface and a Distributed PMIPv6 scheme in order to improve the handover performance and consequently the overall network's performance. We proposed an analytical model and we also conducted a numerical analysis of our approach in this chapter.

Then, in chapter 5, we have proposed our fuzzy logic-based algorithm of selecting the best network candidate for vertical handover denoted PMIP-FL, in order to enhance our proposed PMIP-MIVH approach. In this algorithm, we have defined our proper QoS metric that we called Expected QoS metric, which is based on a tradeoff ratio between the application requirements and the performance capabilities offered by the network.

Then, in the chapter 6, we have presented the implementation and simulation of both the proposed solutions using the well-known and most used Network Simulator version 3 (NS3). We have described and conducted thoroughly the performance metrics in terms of packet delivery ratio (PDR), Packet Error Rate (PER), delay, jitter, and throughput. The simulation results confirmed the analytical results. They show that our proposed PMIP-MIVH approach outperforms the existing solutions. Furthermore, the use of fuzzy logic in PMIP-FL has enhanced the performance of our proposed PMIP-MIVH vertical handover mechanism.

7.2. Perspectives and challenges

Efficient Vertical handover mechanism and LTE enhancements for V2X services support are still needing many efforts in the industrial and academic research fields, and tight collaborations between these two kinds of researchers is considered with great attention for autonomous and smart mobility transportation deployments. Researchers are encouraged to go deeper in this field, in order to propose and find efficient solutions needed for a better deployment of connected and autonomous vehicles, smart mobility, and intelligent transportation.

In the near future, nous voulons continuer à concevoir un algorithme de décision de transfert intercellulaire plus efficace afin d'améliorer les performances des solutions proposées. Thus, our short-term perspectives will focus on :

- The study of the impact of parameters weighting in the Expected QoS metric.
- The test and evaluation of different existing methods used when dealing with fuzzy logic (amomng them are the membership functions, the inference modules, defuzzification methods, etc.)
- The evaluation of the interest in using takagi-sugeno method instead of mamdani, as example the reduction of the number of rules.
- The implementation of our solutions into OBU and table test of them.

Then, our long-term perspectives will focus on :

- Designing a testbed in order to evaluate the proposed solutions in a realistic scenario and consider more real-time parameters and requirements.
- Implementation of the flow mobility extension for an efficient use of resources when the vehicle stays simultaneously connected to at least two networks, for long time.

Furthermore, in order to have a proper and good seamless handover and services in autonomous vehicles, the following challenging issues are still to be solved:

- QoS: the vehicle will almost use real-time and non-real time traffic at any time. Such applications need, then, to be always served with guaranteed QoS, which needs a great number of parameters to be considered.
- TCP performance: in TCP, there are many mechanisms that are used for congestion flow control and which are based on bandwidth and contention window. Thus, in those HVNs, when handover occurs between a low bandwidth and high data rate network to a high bandwidth and low data rate network, the TCP performance may highly be degraded. Special mechanisms have to be developed to resolve this issue.
- Security: since VANETs communications use the Outside of the Context of Basic Service Set (OCB), some Authentication, Authorization, and Accounting (AAA) mechanisms are not taken into account during the communication which can be a source of security issues and hacking attacks. This field has to be well studied in order to ensure the reliability of VANETs communications, especially in handover cases while simultaneously maintaining a reliable and low handover latency and jitter.

- Intelligent routing and path planning: as VANETs present a high mobility and frequent topology changes, efficient handover must highly consider the next position prediction as a main criteria when making handover decisions. It is why path planning is a great challenge that must be resolved in decision making for autonomous vehicles in urban environments because it enables self-driving cars to find the safest, most convenient, and most economically beneficial routes from a depart point to a destination point. Finding routes is complicated by all of the static and maneuverable obstacles that a vehicle must identify and bypass. Effective path planning algorithms are what make autonomous driving genuinely feasible, safe, and fast.Currently, major path planning approaches include the predictive control model, feasible model, and behavior-based model. These approaches must be improved in a way to perfectly and timely get the correct future vehicle position to be used especially during the handover decision phase.

- Sensors & artificial intelligence: vehicle continuously interacts with its environnement through a certain amount of sensors data. These data captured from different sensors need to be fused before being used in making vehicles'decision. Currently, the artificial intelligence is a great core technology that is used in this field and needs to be well tested in different real scenarios before vehicle passengers can confidently use fully self-driving cars.

- Real time massive data processing: a good combination of parrallel and sequential data processing is needed in scenarios, where only parallel data processing is not sufficient. A parallel data acquisition and data processing is needed in handover when considering multiple criteria decision making (MADM).

- Precise location/navigation: when making routing and path planning, a precise location and navigation system is essential. This navigation system must allow also an efficient synchronization between all the components of the transportation system (vehicles, RSU, sensors, lidars, cameras, etc). The navigation system might be enhanced using the sensor sharing and environmental perception approaches in order to well control the vehicle behavior and consequently, predict the relevant future vehicle's position.

- Network services and high edge-computing capabilities: requirements such as latency, reliability, throughput, and scalability must be fulfilled. This also implies and supposes the availability of advanced computing devices and memory within the vehicles or Cloud Computing and Big Data capabilities. Some examples of networks services that could be provided are :

- Cloud services, connection to the internet
- Multi-access Edge Computing (MEC) for critical and non-latency-tolerant applications
- Network assistance for highly accurate positioning

In the long term, we want to also continue dealing with these raised challenges.

Bibliography

[1] WHO. *Global status report on road safety 2018*. URL: https://www.who.int/violence_injury_prevention/road_safety_status/2018/en/.

[2] WHO. *Road Traffic Injuries*. URL: https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries.

[3] Nick Asselin-Miler et al. *Study on the Deployment of C-ITS in Europe: Final Report. Framework Contract on Impact Assessment and Evaluation Studies in the Field of Transport OVE/3/119-2013-Lot no 5 "Horizontal*. Technical report. Feb. 2016. URL: https://ec.europa.eu/transport/sites/transport/files/2016-c-its-deployment-study-final-report.pdf.

[4] O. K. Tonguz and W. Viriyasitavat. "Cars as roadside units: a self-organizing network solution". In: *IEEE Communications Magazine* 51.12 (Dec. 2013), pp. 112–120. ISSN: 0163-6804. DOI: 10.1109/MCOM.2013.6685766.

[5] Thomas L. Saaty. "Decision making — the Analytic Hierarchy and Network Processes (AHP/ANP)". In: *Journal of Systems Science and Systems Engineering* 13.1 (Mar. 2004), pp. 1–35. ISSN: 1861-9576. DOI: 10.1007/s11518-006-0151-5. URL: https://doi.org/10.1007/s11518-006-0151-5.

[6] Thomas L. Saaty. "Relative measurement and its generalization in decision making why pairwise comparisons are central in mathematics for the measurement of intangible factors the analytic hierarchy/network process". In: *RACSAM - Revista de la Real Academia de Ciencias Exactas, Fisicas y Naturales. Serie A. Matematicas* 102.2 (Sept. 2008), pp. 251–318. ISSN: 1579-1505. DOI: 10.1007/BF03191825. URL: https://doi.org/10.1007/BF03191825.

[7] Omkarprasad S. Vaidya and Sushil Kumar. "Analytic hierarchy process: An overview of applications". In: *European Journal of Operational Research* 169.1 (2006), pp. 1–29. ISSN: 0377-2217. DOI: https://doi.org/10.1016/j.ejor.2004.04.028. URL: http://www.sciencedirect.com/science/article/pii/S0377221704003054.

[8] Nieves Espinosa et al. "Towards low-cost manufacturing of organic solar cells: multi-criteria assessment of fabrication technologies". In: *Renewable Energy and Power Quality Journal* 1 (Mar. 2010). DOI: 10.24084/repqj08.547.

[9] Giorgio Locatelli and Mauro Mancini. "A framework for the selection of the right nuclear power plant". In: *International Journal of Production Research* 50.17 (2012), pp. 4753–4766. DOI: 10.1080/00207543.2012.657965. eprint: https://doi.org/10.1080/00207543.2012.657965. URL: https://doi.org/10.1080/00207543.2012.657965.

[10] Burak Omer Saracoglu. "Selecting industrial investment locations in master plans of countries". In: *European Journal of Industrial Engineering* 7.4 (2013), pp. 416–441. URL: https://ideas.repec.org/a/ids/eujine/v7y2013i4p416-441.html.

[11] Jayaram C Sasi and Dr. Abhijeet K Digalwar. "Application of AHP and TOPSIS Method for Supplier Selection Between India and China in Textile Industry". In: 2015.

[12] Maria Berrittella et al. *An Analytic Hierarchy Process for The Evaluation of Transport Policies to Reduce Climate Change Impacts*. Climate Change Modelling and Policy Working Papers 10264. Fondazione Eni Enrico Mattei (FEEM), 2007. URL: https://ideas.repec.org/p/ags/feemcc/10264.html.

[13] Johann Márquez-Barja et al. "An overview of vertical handover techniques: Algorithms, protocols and tools". In: *Computer Communications* 34.8 (2011), pp. 985–997. ISSN: 0140-3664. DOI: https://doi.org/10.1016/j.comcom.2010.11.010. URL: http://www.sciencedirect.com/science/article/pii/S0140366410004834.

[14] Meriem Kassar, Brigitte Kervella, and Guy Pujolle. "An overview of vertical handover decision strategies in heterogeneous wireless networks". In: *Computer Communications* 31.10 (2008), pp. 2607–2620. ISSN: 0140-3664. DOI: https://doi.org/10.1016/j.comcom.2008.01.044. URL: http://www.sciencedirect.com/science/article/pii/S0140366408000492.

[15] Fatma Betül Yeni and Gökhan Özçelik. "Interval-Valued Atanassov Intuitionistic Fuzzy CODAS Method for Multi Criteria Group Decision Making Problems". In: *Group Decision and Negotiation* 28.2 (Apr. 2019), pp. 433–452. ISSN: 1572-9907. DOI: 10.1007/s10726-018-9603-9. URL: https://doi.org/10.1007/s10726-018-9603-9.

[16] L. Xia, L. -. Jiang, and C. He. "A Novel Fuzzy Logic Vertical Handoff Algorithm with Aid of Differential Prediction and Pre-Decision Method". In: *2007 IEEE International Conference on Communications*. June 2007, pp. 5665–5670. DOI: 10.1109/ICC.2007.939.

[17] Erdal Kayacan and Mojtaba Ahmadieh Khanesar. "Chapter 2 - Fundamentals of Type-1 Fuzzy Logic Theory". In: *Fuzzy Neural Networks for Real Time Control Applications*. Ed. by Erdal Kayacan and Mojtaba Ahmadieh Khanesar. Butterworth-Heinemann, 2016, pp. 13–24. ISBN: 978-0-12-802687-8. DOI: https://doi.org/10.1016/B978-0-12-802687-8.00002-5. URL: http://www.sciencedirect.com/science/article/pii/B9780128026878000025.

[18] A. Ahmed, L. M. Boulahia, and D. Gaiti. "Enabling Vertical Handover Decisions in Heterogeneous Wireless Networks: A State-of-the-Art and A Classification". In: *IEEE Communications Surveys Tutorials* 16.2 (2014), pp. 776–811. ISSN: 1553-877X. DOI: 10.1109/SURV.2013.082713.00141.

[19] Livinus Tuyisenge et al. "A Soft Logical Interface PMIPv6-based Handover Mechanism in VANETs". In: *2019 IEEE Global Communications Conference: Communications Software,Services and Multimedia Apps (Globecom2019 CSSMA)*. Waikoloa, USA, Dec. 2019.

[20] ITU-T. *Vocabulary for performance, quality of service and quality of experience (P.10/G.100)*. Nov. 2017. URL: https://www.itu.int/rec/T-REC-P.10-201711-I.

[21] M. Fiedler, T. Hossfeld, and P. Tran-Gia. "A generic quantitative relationship between quality of experience and quality of service". In: *IEEE Network* 24.2 (Mar. 2010), pp. 36–41. ISSN: 0890-8044. DOI: 10.1109/MNET.2010.5430142.

[22] Knut Evensen. *IEEE 802 CALM Tutorial*. Accessed on 2019-08-15. URL: http://grouper.ieee.org/groups/802/802_tutorials/06-November/.

[23] Zach Shelby, Klaus Hartke, and Carsten Bormann. *The Constrained Application Protocol (CoAP)*. RFC 7252. June 2014. DOI: 10.17487/RFC7252. URL: https://rfc-editor.org/rfc/rfc7252.txt.

[24] ISO. *Information technology — Message Queuing Telemetry Transport (MQTT) v3.1.1*. Accessed on 2019-08-15. URL: https://www.iso.org/standard/69466.html.

[25] Open Mobile Alliance. *Open Mobile Alliance Device Management.* Accessed on 2019-08-08. URL: http://www.openmobilealliance.org/release/DM/V2_0-20160209-A/.

[26] *ETSI EN 302 636-4-1; Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4: Geographical Addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 1: Media-Independent Functionality.* 302 636-4-1 (European Standard). July 2014.

[27] *Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band.* ETSI ES 202 663 (ETSI Standard). Nov. 2009.

[28] *ETSI EN 302 637-2; Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service.* 302 637-2 (European Standard). Nov. 2014.

[29] *ETSI EN 302 637-3; Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Application; Part 3: Specifications of Decentralized Environmental Notification Basic Service.* 302 697-3 (European Standard). Nov. 2014.

[30] M. Gerla et al. "Internet of vehicles: From intelligent grid to autonomous cars and vehicular clouds". In: *2014 IEEE World Forum on Internet of Things (WF-IoT)*. Mar. 2014, pp. 241–246. DOI: 10.1109/WF-IoT.2014.6803166.

[31] Juan Contreras-Castillo, Sherali Zeadally, and Juan Antonio Guerrero Ibáñez. "A seven-layered model architecture for Internet of Vehicles". In: *Journal of Information and Telecommunication* 1.1 (2017), pp. 4–22. DOI: http://dx.doi.org/10.1080/24751839.2017.1295601. URL: http://www.tandfonline.com/doi/pdf/10.1080/24751839.2017.1295601.

[32] Paolo Bellavista et al. "A survey on fog computing for the Internet of Things". In: *Pervasive and Mobile Computing* 52 (2019), pp. 71–99. ISSN: 1574-1192. DOI: https://doi.org/10.1016/j.pmcj.2018.12.007. URL: http://www.sciencedirect.com/science/article/pii/S1574119218301111.

[33] Flavio Bonomi. *The smart and connected vehicle and the Internet of Things*. Seminars. Cisco Systems:Advanced Architectures and Research, WSTS, San Jose, 2013. URL: http://tf.nist.gov/seminars/WSTS/PDFs/1-0_Cisco_FBonomi_ConnectedVehicles.pdf.

[34] O. Kaiwartya et al. "Internet of Vehicles: Motivation, Layered Architecture, Network Model, Challenges, and Future Aspects". In: *IEEE Access* 4 (Sept. 2016), pp. 5356–5373. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2016.2603219.

[35] Liu Nanjie. *Internet of Vehicles: Your next connection*. 2011. URL: http://www1.huawei.com/enapp/28/hw-110836.htm.

[36] Pimmy Gandotra, Rakesh Kumar Jha, and Sanjeev Jain. "A survey on device-to-device (D2D) communication: Architecture and security issues". In: *Journal of Network and Computer Applications* 78 (2017), pp. 9–29. ISSN: 1084-8045. DOI: https://doi.org/10.1016/j.jnca.2016.11.002. URL: http://www.sciencedirect.com/science/article/pii/S1084804516302727.

[37] J. Wan et al. "Context-aware vehicular cyber-physical systems with cloud support: architecture, challenges, and solutions". In: *IEEE Communications Magazine* 52.8 (Aug. 2014), pp. 106–113. ISSN: 0163-6804. DOI: 10.1109/MCOM.2014.6871677.

[38] L. Kang et al. "A traffic-aware resource allocation scheme for internet of vehicles: A supply and demand function approach". In: *Journal of Computational Information Systems* 11.3 (Feb. 2015), pp. 987–994. ISSN: 1687-1499. DOI: 10.12733/jcis13115. URL: https://www.researchgate.net/publication/281704933_A_traffic-aware_resource_allocation_scheme_for_internet_of_vehicles_A_supply_and_demand_function_approach/citations.

[39] L. Alouache et al. "Toward a hybrid SDN architecture for V2V communication in IoV environment". In: *2018 Fifth International Conference on Software Defined Systems (SDS)*. Apr. 2018, pp. 93–99. DOI: 10.1109/SDS.2018.8370428.

[40] T. S. J. Darwish and K. Abu Bakar. "Fog Based Intelligent Transportation Big Data Analytics in The Internet of Vehicles Environment: Motivations, Architecture, Challenges, and Critical Issues". In: *IEEE Access* 6 (2018), pp. 15679–15701. DOI: 10.1109/ACCESS.2018.2815989.

[41] Nathan Marz and James Warren. *Big Data:Principles and best practices of scalable realtime data systems*. Shelter Island, NY, USA: Manning Publications, Apr. 2015. ISBN: 9781617290343.

[42] "IEEE Standard for Local and metropolitan area networks–Part 21: Media Independent Services Framework–Corrigendum 1: Clarification of Parameter Definition in Group Session Key Derivation". In: *IEEE Std 802.21-2017/Cor 1-2017 (Corrigendum to IEEE Std 802.21-2017)* (Jan. 2018), pp. 1–13. DOI: 10.1109/IEEESTD.2018.8275476.

[43] Mehmet Fatih Tuysuz and Ramona Trestian. "Energy-Efficient Vertical Handover Parameters, Classification and Solutions over Wireless Heterogeneous Networks: A Comprehensive Survey". In: *Wireless Personal Communications* 97.1 (Nov. 2017), pp. 1155–1184. ISSN: 1572-834X. DOI: 10.1007/s11277-017-4559-7. URL: https://doi.org/10.1007/s11277-017-4559-7.

[44] Shidrokh Goudarzi et al. "A Comparative Review of Vertical Handover Decision-Making Mechanisms in Heterogeneous Wireless Networks". In: *Indian Journal of Science and Technology* 8.23 (2015). ISSN: 0974 -5645. URL: http://www.indjst.org/index.php/indjst/article/view/57183.

[45] I. Ali et al. "Network-based mobility management in the evolved 3GPP core network". In: *IEEE Communications Magazine* 47.2 (Feb. 2009), pp. 58–66. ISSN: 0163-6804. DOI: 10.1109/MCOM.2009.4785381.

[46] I. F. Akyildiz, Jiang Xie, and S. Mohanty. "A survey of mobility management in next-generation all-IP-based wireless systems". In: *IEEE Wireless Communications* 11.4 (Aug. 2004), pp. 16–28. ISSN: 1536-1284. DOI: 10.1109/MWC.2004.1325888.

[47] Dapeng Liu et al. *Distributed Mobility Management: Current Practices and Gap Analysis*. RFC 7429. Jan. 2015. DOI: 10.17487/RFC7429. URL: https://rfc-editor.org/rfc/rfc7429.txt.

[48] Ed. D. Thaler et al. *IETF RFC 6724 (September 2012):Default Address Selection for Internet Protocol Version 6 (IPv6)*. Tech. rep. Sept. 2012.

[49] M. Le Pape and S. Bhandari. *IETF Internet Draft (July 2015): IPv6 Prefix Meta-data and Usage, draft-lepape-6man-prefix-metadata-00.* Tech. rep. July 2015.

[50] RFC5944. *IETF RFC 5944 (November 2010):IP Mobility Support for IPv4, Revised*. Tech. rep. Nov. 2010.

[51] David B. Johnson, Jari Arkko, and Charles E. Perkins. *Mobility Support in IPv6*. RFC 6275. Updated on 2015-10-14, Accessed Online: 2019-07-23. July 2011. DOI: 10.17487/RFC6275. URL: https://rfc-editor.org/rfc/rfc6275.txt.

[52] S. Gundavelli et al. *Proxy Mobile IPv6*. En. RFC 5213. Updated by RFC 7864, RFC 6543. IETF, Aug. 2008. URL: https://datatracker.ietf.org/doc/rfc5213/.

[53] Carlos J. Bernardos. *Proxy Mobile IPv6 Extensions to Support Flow Mobility*. RFC 7864. May 2016. DOI: 10.17487/RFC7864. URL: https://rfc-editor.org/rfc/rfc7864.txt.

[54] Pascal Thubert et al. *Network Mobility (NEMO) Basic Support Protocol*. RFC 3963. Updated on 2013-03-02, Accessed online: 2019-07-23. Jan. 2005. DOI: 10.17487/RFC3963. URL: https://rfc-editor.org/rfc/rfc3963.txt.

[55] RFC4960. *IETF RFC 4960 (October 2008):Stream Control Transmission Protocol*. Tech. rep. Sept. 2007.

[56] RFC5380. *IETF RFC 5380 (October 2008):Hierarchical Mobile IPv6 (HMIPv6) Mobility Management*. Tech. rep. Oct. 2008.

[57] Z. Dai et al. "Vertical Handover Criteria and Algorithm in IEEE802.11 and 802.16 Hybrid Networks". In: *2008 IEEE International Conference on Communications*. May 2008, pp. 2480–2484. DOI: 10.1109/ICC.2008.470.

[58] RFC5568. *IETF RFC 5568 (July 2009):Mobile IPv6 Fast Handovers*. Tech. rep. July 2009.

[59] Ed. R. Koodli. *IETF RFC 5568 (July 2009):Mobile IPv6 Fast Handovers*. Tech. rep. June 2008.

[60] Ed. P. Eronen. *IETF RFC 4555 (June 2006):IKEv2 Mobility and Multihoming Protocol (MOBIKE)*. Tech. rep. June 2006.

[61] J. I. Kim and S. J. Koh. "Distributed mobility management in proxy mobile IPv6 using hash function". In: *The International Conference on Information Networking 2013 (ICOIN)*. Jan. 2013, pp. 107–112. DOI: 10.1109/ICOIN.2013.6496360.

[62] Heeyoung Jung et al. "Distributed Mobility Control in Proxy Mobile IPv6 Networks". In: *IEICE Transactions* 94-B (Aug. 2011), pp. 2216–2224. DOI: 10.1587/transcom.E94.B.2216.

[63] Hidetoshi Yokota et al. *Fast Handovers for Proxy Mobile IPv6*. RFC 5949. Sept. 2010. DOI: 10.17487/RFC5949. URL: https://rfc-editor.org/rfc/rfc5949.txt.

[64] H. Y. Choi et al. "Implementation and Evaluation of Proxy Mobile IPv6 in NS-3 Network Simulator". In: *2010 Proceedings of the 5th International Conference on Ubiquitous Information Technologies and Applications*. Dec. 2010, pp. 1–6. DOI: 10.1109/ICUT.2010.5677817.

[65] Telemaco Melia and Sri Gundavelli. *Logical-Interface Support for IP Hosts with Multi-Access Support*. RFC 7847. May 2016. DOI: 10.17487/RFC7847. URL: https://rfc-editor.org/rfc/rfc7847.txt.

[66] Robert T. Braden. *Requirements for Internet Hosts - Communication Layers*. RFC 1122. Oct. 1989. DOI: 10.17487/RFC1122. URL: https://rfc-editor.org/rfc/rfc1122.txt.

[67] T. M. Trung et al. "A design of network-based flow mobility based on proxy mobile IPv6". In: *2011 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. Apr. 2011, pp. 373–378. DOI: 10.1109/INFCOMW.2011.5928841.

[68] K. Xie, J. Lin, and L. Wu. "Design and Implementation of Flow Mobility Based on D-PMIPv6". In: *2014 IEEE 17th International Conference on Computational Science and Engineering*. Dec. 2014, pp. 1344–1349. DOI: 10.1109/CSE.2014.256.

[69] Y. G. Hong et al. "Analysis of the usage of a logical interface in PMIPv6". In: *13th International Conference on Advanced Communication Technology (ICACT2011)*. Feb. 2011, pp. 1069–1074.

[70] Shun-Neng Yang et al. "A Multi-link Mechanism for Heterogeneous Radio Networks". In: *Wireless Personal Communications* 76.4 (June 2014), pp. 661–674. ISSN: 1572-834X. DOI: 10.1007/s11277-013-1357-8. URL: https://doi.org/10.1007/s11277-013-1357-8.

[71] Rostislav Lisový, Michal Sojka, and Zdeněk Hanzálek. *IEEE 802.11p Linux Kernel Implementation*. online. Dec. 2014. DOI: 10.17487/RFC1122. URL: https://rtime.felk.cvut.cz/publications/public/ieee80211p_linux_2014_final_report.pdf.

[72] Vivek Jain et al. "Implementation and validation of BLUE and PI queue disciplines in ns-3". In: *Simulation Modelling Practice and Theory* 84 (2018), pp. 19–37. ISSN: 1569-190X. DOI: https://doi.org/10.1016/j.simpat.2018.01.002. URL: http://www.sciencedirect.com/science/article/pii/S1569190X18300029.

[73] S. E. Kim and J. A. Copeland. "TCP for seamless vertical handoff in hybrid mobile data networks". In: *Global Telecommunications Conference, 2003. GLOBECOM '03. IEEE*. Vol. 2. Dec. 2003, 661–665 Vol.2. DOI: 10.1109/GLOCOM.2003.1258321.

[74] Arifumi Matsumoto, Kenji Fujikawa Masahiro Kozuka, and Yasuo Okabe. *IETF Internet Draft (october 2003): TCP Mlti-Home options, draft-arifumi-tcp-mh-00.txt.* Tech. rep. Oct. 2003.

[75] Ling-Jyh Chen et al. "A Smart Decision Model for Vertical Handoff". In: *Proc ANWIRE*. 2004.

[76] Yanmin Zhu, Lei Ni, and Bo Li. "Exploiting mobility patterns for inter-technology handover in mobile environments". In: *Computer Communications* 36.2 (2013), pp. 203–210. ISSN: 0140-3664. DOI: https://doi.org/10.1016/j.comcom.2012.08.016. URL: http://www.sciencedirect.com/science/article/pii/S0140366412002927.

[77] Salih K. Yass et al. "A novel noncooperative game competing model using generalized simple additive weighting method to perform network selection in heterogeneous wireless networks". In: *International Journal of Communication Systems* 28.6 (Apr. 2015), pp. 1112–1125. DOI: 10.1002/dac.2747. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/dac.2747. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/dac.2747.

[78] Li Yi et al. "D-PMIPv6: A distributed mobility management scheme supported by data and control plane separation". In: *Mathematical and Computer Modelling* 58.5 (2013). The Measurement of Undesirable Outputs: Models Development and Empirical Analyses and Advances in mobile, ubiquitous and cognitive computing, pp. 1415–1426. ISSN: 0895-7177. DOI: https://doi.org/10.1016/j.mcm.2012.11.031. URL: http://www.sciencedirect.com/science/article/pii/S0895717712003445.

[79] RFC2960. *IETF RFC 2960 (october 2000): Stream Control Transmission Protocol*. Tech. rep. Oct. 2000.

[80] RFC7053. *IETF RFC 7053 (November 2013): SACK-IMMEDIATELY Extension for the Stream Control Transmission Protocol*. Tech. rep. Nov. 2013.

[81] O. Ormond, J. Murphy, and G. m. Muntean. "Utility-based Intelligent Network Selection in Beyond 3G Systems". In: *2006 IEEE International Conference on Communications*. Vol. 4. June 2006, pp. 1831–1836. DOI: 10.1109/ICC.2006.254986.

[82] Z. Dai et al. "Vertical Handover Criteria and Algorithm in IEEE802.11 and 802.16 Hybrid Networks". In: *2008 IEEE International Conference on Communications*. May 2008, pp. 2480–2484. DOI: 10.1109/ICC.2008.470.

[83] Q. t. Nguyen-Vuong, N. Agoulmine, and Y. Ghamri-Doudane. "Terminal-Controlled Mobility Management in Heterogeneous Wireless Networks". In: *IEEE Communications Magazine* 45.4 (Apr. 2007), pp. 122–129. ISSN: 0163-6804. DOI: 10.1109/MCOM.2007.343621.

[84] Marc Emmelmann, Tim Langgäertner, and Marcus Sonnemann. "System design and implementation of seamless handover support enabling real-time telemetryhighly mobile users". In: *Proceedings of the Sixth ACM International Workshop on Mobility Management & Wireless Access, MOBIWAC 2008, Vancouver, British Columbia, Canada, October 30-31, 2008*. 2008, pp. 1–8. DOI: 10.1145/1454659.1454661. URL: http://doi.acm.org/10.1145/1454659.1454661.

[85] Adiline T. Macriga and P. Anandha Kumar. "Mobility Management for Seamless Information flow in Heterogeneous Networks Using Hybrid Handover". In: Oct. 2010.

[86] Mohamed Alnas, Irfan Awan, and D. R. W. Holton. "Enhanced Mobile IP Handoff Using Link Layer Information". In: *Proceedings of the 11th International Conference on Information Integration and Web-based Applications &Amp; Services*. iiWAS '09. Kuala Lumpur, Malaysia: ACM, 2009, pp. 344–349. ISBN: 978-1-60558-660-1. DOI: 10.1145/1806338.1806401. URL: http://doi.acm.org/10.1145/1806338.1806401.

[87] Joon-Myung Kang et al. "Autonomic personalized handover decisions for mobile services in heterogeneous wireless networks". In: *Computer Networks* 55.7 (2011). Recent Advances in Network Convergence, pp. 1520–1532. ISSN: 1389-1286. DOI: https://doi.org/10.1016/j.comnet.2011.01.021. URL: http://www.sciencedirect.com/science/article/pii/S1389128611000442.

[88] B. J. Chang and J. F. Chen. "Cross-Layer-Based Adaptive Vertical Handoff With Predictive RSS in Heterogeneous Wireless Networks". In: *IEEE Transactions on Vehicular Technology* 57.6 (Nov. 2008), pp. 3679–3692. ISSN: 0018-9545. DOI: 10.1109/TVT.2008.921619.

[89] Soohong Park, Jaehoon (Paul) Jeong, and Choong Seon Hong. "QoS-guaranteed Mobile IPTV service in heterogeneous access networks". In: *Computer Networks* 69 (2014), pp. 66–81. ISSN: 1389-1286. DOI: ht

tps://doi.org/10.1016/j.comnet.2014.04.021. URL: http://www.sciencedirect.com/science/article/pii/S1389128614001844.

[90] B. K. Kim et al. "Enhanced FMIPv4 Horizontal Handover with Minimized Channel Scanning Time Based on Media Independent Handover (MIH)". In: *NOMS Workshops 2008 - IEEE Network Operations and Management Symposium Workshops*. Apr. 2008, pp. 52–55. DOI: 10.1109/NOMSW.2007.11.

[91] Tsungnan Lin, Chiapin Wang, and Po-Chiang Lin. "A Neural-network-based Context-aware Handoff Algorithm for Multimedia Computing". In: *ACM Trans. Multimedia Comput. Commun. Appl.* 4.3 (Sept. 2008), 17:1–17:23. ISSN: 1551-6857. DOI: 10.1145/1386109.1386110. URL: http://doi.acm.org/10.1145/1386109.1386110.

[92] Vijay T Raisinghani and Sridhar Iyer. "Cross-layer design optimizations in wireless protocol stacks". In: *Computer Communications* 27.8 (2004). Advances in Future Mobile/Wireless Networks and Services, pp. 720–724. ISSN: 0140-3664. DOI: https://doi.org/10.1016/j.comcom.2003.10.011. URL: http://www.sciencedirect.com/science/article/pii/S0140366403002913.

[93] Ioannis Chamodrakas and Drakoulis Martakos. "A Utility-based Fuzzy TOPSIS Method for Energy Efficient Network Selection in Heterogeneous Wireless Networks". In: *Appl. Soft Comput.* 12.7 (July 2012), pp. 1929–1938. ISSN: 1568-4946. DOI: 10.1016/j.asoc.2012.04.016. URL: http://dx.doi.org/10.1016/j.asoc.2012.04.016.

[94] Chih-Peng Lin, Hsing-Lung Chen, and Jenq-Shiou Leu. "A Predictive Handover Scheme to Improve Service Quality in the IEEE 802.21 Network". In: *Comput. Electr. Eng.* 38.3 (May 2012), pp. 681–693. ISSN: 0045-7906. DOI: 10.1016/j.compeleceng.2012.02.013. URL: http://dx.doi.org/10.1016/j.compeleceng.2012.02.013.

[95] Cheng Wei Lee et al. "A framework of handoffs in wireless overlay networks based on mobile IPv6". In: *IEEE Journal on Selected Areas in Communications* 23.11 (Nov. 2005), pp. 2118–2128. ISSN: 0733-8716. DOI: 10.1109/JSAC.2005.856833.

[96] I. Joe and M. Shin. "A Mobility-Based Prediction Algorithm with Dynamic LGD Triggering for Vertical Handover". In: *2010 7th IEEE Consumer Communications and Networking Conference*. Jan. 2010, pp. 1–2. DOI: 10.1109/CCNC.2010.5421627.

[97] Fang Zhu and Janise McNair. "Multiservice Vertical Handoff Decision Algorithms". In: *EURASIP J. Wirel. Commun. Netw.* 2006.2 (Apr. 2006), pp. 52–52. ISSN: 1687-1472. DOI: 10.1155/WCN/2006/25861. URL: http://dx.doi.org/10.1155/WCN/2006/25861.

[98] R. Tawil, O. Salazar, and G. Pujolle. "Vertical Handoff Decision Scheme Using MADM for Wireless Networks". In: *2008 IEEE Wireless Communications and Networking Conference*. Mar. 2008, pp. 2789–2792. DOI: 10.1109/WCNC.2008.488.

[99] D. Giacomini and A. Agarwal. "Vertical handover decision making using QoS reputation and GM(1,1) prediction". In: *2012 IEEE International Conference on Communications (ICC)*. June 2012, pp. 5655–5659. DOI: 10.1109/ICC.2012.6364807.

[100] Anastasios A. Kikilis and Angelos N. Rouskas. "Formulation of optimization problems for access selection in next generation wireless networks". In: *Proceedings of the 3rd International Conference on Mobile Multimedia Communications, MobiMedia 2007, Nafpaktos, Greece, August 27-29, 2007*. 2007, p. 21. DOI: 10.4108/ICST.MOBIMEDIA2007.1732. URL: https://doi.org/10.4108/ICST.MOBIMEDIA2007.1732.

[101] Maaz Rehan et al. "A Cross-Layer User Centric Vertical Handover Decision Approach Based on MIH Local Triggers". In: *Wireless and Mobile Networking*. Ed. by Jozef Wozniak et al. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 359–369. ISBN: 978-3-642-03841-9.

[102] Y. Wang et al. "Vertical Handover Decision in an Enhanced Media Independent Handover Framework". In: *2008 IEEE Wireless Communications and Networking Conference*. Mar. 2008, pp. 2693–2698. DOI: 10.1109/WCNC.2008.472.

[103] E. Stevens-Navarro, V. W. S. Wong, and Y. Lin. "A Vertical Handoff Decision Algorithm for Heterogeneous Wireless Networks". In: *2007 IEEE Wireless Communications and Networking Conference*. Mar. 2007, pp. 3199–3204. DOI: 10.1109/WCNC.2007.590.

[104] Zhaolong Ning et al. "Markov-based vertical handoff decision algorithms in heterogeneous wireless networks". In: *Computers & Electrical Engineering* 40.2 (2014), pp. 456–472. ISSN: 0045-7906. DOI: https://doi.org/10.1016/j.compeleceng.2013.10.012. URL: http://www.sciencedirect.com/science/article/pii/S0045790613002607.

[105] Yuzo Taenaka et al. "An implementation design of a cross-layer handover method with multi-path transmission for VoIP communication". In: *Ad Hoc Networks* 13 (2014), pp. 462–475. ISSN: 1570-8705. DOI: https://doi.org/10.1016/j.adhoc.2013.10.002. URL: http://www.sciencedirect.com/science/article/pii/S1570870513002072.

[106] S. Mohanty and I. F. Akyildiz. "A Cross-Layer (Layer 2 + 3) Handoff Management Protocol for Next-Generation Wireless Systems". In: *IEEE Transactions on Mobile Computing* 5.10 (Oct. 2006), pp. 1347–1360. ISSN: 1536-1233. DOI: 10.1109/TMC.2006.142.

[107] L. Shan et al. "Predictive Group Handover Scheme with Channel Borrowing for Mobile Relay Systems". In: *2008 International Wireless Communications and Mobile Computing Conference*. Aug. 2008, pp. 153–158. DOI: 10.1109/IWCMC.2008.27.

[108] Ramona Trestian, Olga Ormond, and Gabriel-Miro Muntean. "Reputation-based network selection mechanism using game theory". In: *Physical Communication* 4.3 (2011). Recent Advances in Cooperative Communications for Wireless Systems, pp. 156–171. ISSN: 1874-4907. DOI: https://doi.org/10.1016/j.phycom.2011.06.004. URL: http://www.sciencedirect.com/science/article/pii/S1874490711000322.

[109] F. Giust, L. Cominardi, and C. J. Bernardos. "Distributed mobility management for future 5G networks: overview and analysis of existing approaches". In: *IEEE Communications Magazine* 53.1 (Jan. 2015), pp. 142–149. ISSN: 0163-6804. DOI: 10.1109/MCOM.2015.7010527.

[110] Anthony Chan et al. *Requirements for Distributed Mobility Management*. RFC 7333. Accessed online: 2019-07-23. Aug. 2014. DOI: 10.17487/RFC7333. URL: https://rfc-editor.org/rfc/rfc7333.txt.

[111] RFC6463. *IETF RFC 6463 (February 2012):Runtime Local Mobility Anchor (LMA) Assignment Support for Proxy Mobile IPv6*. Tech. rep. Feb. 2012.

[112] RFC6705. *IETF RFC 6705 (September 2012): Localized Routing for Proxy Mobile IPv6*. Tech. rep. Sept. 2012.

[113] RFC6097. *IETF RFC 6097 (February 2011): Local Mobility Anchor (LMA) Discovery for Proxy Mobile IPv6*. Tech. rep. Feb. 2011.

[114] M. K. Murtadha et al. "Fully distributed mobility management scheme for future heterogeneous wireless networks". In: *2015 IEEE 12th Malaysia International Conference on Communications (MICC)*. Nov. 2015, pp. 270–275. DOI: 10.1109/MICC.2015.7725446.

[115] Muayad Khalil Murtadha et al. "Design and evaluation of distributed and dynamic mobility management approach based on PMIPv6 and MIH protocols". In: *Wireless Networks* 21.8 (2015), pp. 2747–2763. ISSN: 1572-8196. DOI: 10.1007/s11276-015-0950-z. URL: http://dx.doi.org/10.1007/s11276-015-0950-z.

[116] L. Zanzi, F. Giust, and V. Sciancalepore. "M2EC: A multi-tenant resource orchestration in multi-access edge computing systems". In: *2018 IEEE Wireless Communications and Networking Conference (WCNC)*. Apr. 2018, pp. 1–6. DOI: 10.1109/WCNC.2018.8377292.

[117] G. Li et al. "Service Popularity-based Smart Resources Partitioning for Fog Computing-enabled Industrial Internet of Things". In: *IEEE Transactions on Industrial Informatics* (2018), pp. 1–1. ISSN: 1551-3203. DOI: 10.1109/TII.2018.2845844.

[118] Y. Li et al. "Dynamic mobile cloudlet clustering for fog computing". In: *2018 International Conference on Electronics, Information, and Communication (ICEIC)*. Jan. 2018, pp. 1–4. DOI: 10.23919/ELINFOCOM.2018.8330676.

[119] F. Giust, C. J. Bernardos, and A. de la Oliva. "Analytic Evaluation and Experimental Validation of a Network-Based IPv6 Distributed Mobility Management Solution". In: *IEEE Transactions on Mobile Computing* 13.11 (Nov. 2014), pp. 2484–2497. ISSN: 1536-1233. DOI: 10.1109/TMC.2014.2307304.

[120] Carlos Jésus Bernardos et al. *Proxy Mobile IPv6 extensions for Distributed Mobility Management*. Internet-Draft draft-bernardos-dmm-pmipv6-dlif-00. Work in Progress. Internet Engineering Task Force, Oct. 2017. 30 pp. URL: https://datatracker.ietf.org/doc/html/draft-bernardos-dmm-pmipv6-dlif-00.

[121] O. Sadov et al. "OpenFlow SDN testbed for Storage Area Network". In: *2014 International Science and Technology Conference (Modern Networking Technologies) (MoNeTeC)*. Oct. 2014, pp. 1–3. DOI: 10.1109/MoNeTeC.2014.6995598.

[122] J. R. de Almeida Amazonas, G. Santos-Boada, and J. Solé-Pareta. "A critical review of OpenFlow/SDN-based networks". In: *2014 16th International Conference on Transparent Optical Networks (ICTON)*. July 2014, pp. 1–5. DOI: 10.1109/ICTON.2014.6876509.

[123] Mohamed Lahby, Silki Baghla, and Abderrahim Sekkaki. "Survey and comparison of MADM methods for network selection access in heterogeneous networks". In: *2015 7th International Conference on New Technologies, Mobility and Security (NTMS)* (2015). online: Accessed on 26 Aug 2019, pp. 1–6. URL: https://www.researchgate.net/publication/315719905.

[124] Chris Pudney, Maurice Pope, and ETSI. *ETSI TS 123.401: LTE; General Packet Radio Service (GPRS) enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) access (3GPP TS 23.401 version 11.4.0 Release 11)*. Technical Specifications. Jan. 2013.

[125] Himke van der Velde. "Control Plane Protocols". In: *LTE – The UMTS Long Term Evolution:From Theory to Practice*. John Wiley and Sons, Ltd, 2009, pp. 51–78. ISBN: 9780470742891. DOI: 10.1002/9780470742891.ch3. URL: http://dx.doi.org/10.1002/9780470742891.ch3.

[126] A. Kuzmanovic et al. *IETF RFC 5562 (June 2009): Adding Explicit Congestion Notification (ECN) Capability to TCP's SYN/ACK Packets*. Tech. rep. June 2009.

[127] J. Huang and J. Wang. "An ECN-Based Congestion Control Algorithm for TCP Enhancement in WLAN". In: *2009 11th IEEE International Conference on High Performance Computing and Communications*. June 2009, pp. 464–469. DOI: 10.1109/HPCC.2009.38.

[128] H. -s. Liu, K. Xu, and M. -w. Xu. "A Novel ECN-Based Congestion Control and Avoidance Algorithm with Forecasting and Verifying". In: *Telecommunications and Networking - ICT 2004*. Ed. by José Neuman de Souza, Petre Dini, and Pascal Lorenz. Berlin, Heidelberg: Springer Berlin Heidelberg, 2004, pp. 199–206. ISBN: 978-3-540-27824-5.

[129] Xiaolong Li and Homayoun Yousefi'zadeh. "Distributed ECN-based Congestion Control". In: *Proceedings of the 2009 IEEE International Conference on Communications*. ICC'09. Dresden, Germany: IEEE Press, 2009, pp. 2230–2235. ISBN: 978-1-4244-3434-3. URL: http://dl.acm.org/citation.cfm?id=1817271.1817686.

[130] T. Narten et al. *IETF RFC 4861 (September 2007): Neighbor Discovery for IP version 6 (IPv6)*. Tech. rep. Sept. 2007.

[131] S. Krishnan, J. Korhonen, and A. Yourtchenko S. Chakrabarti E. Nordmark. *Support for Adjustable Maximum Router Lifetimes per Link*. Tech. rep. Feb. 2018.

[132] ETSI. *ETSI TS 123.402: Universal Mobile Telecommunications System (UMTS); LTE; Architecture enhancements for non-3GPP accesses (3GPP TS 23.402 V10.4.0)*. Technical Specifications. June 2011.

[133] ETSI. *LTE;Evolved Universal Terrestrial Radio Access Network (E-UTRAN);S1 Application Protocol (S1AP) (3GPP TS 36.413 version 10.5.0 Release 10)*. Technical Specifications. Mar. 2012.

[134] ETSI. *ETSI TS 136.331: LTE, Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource control(RRC); Protocol specification, (3GPP TS 36.331 version 8.6.0 Release 8)*. Technical Specifications. July 2009.

[135] ETSI. *3GPP TS 136.214 : LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer ; Measurements*. Tech. rep. Apr. 2017.

[136] 3GPP TS GRAN. *ETSI TS 136.133: LTE, Evolved Universal Terrestrial Radio Access (E-UTRA); Requirements for support of radio resource management, (3GPP TS 36.331 version 8.3.0 Release 8)*. Technical Specifications. Sept. 2008.

[137] V. Srinivasa Rao and Rambabu Gajula. *Interoperable UE Handovers in LTE*. Tech. rep. ContinuousComputing, May 2015. URL: http://go.ccpu.com/rs/CCPU/images/wp-interoperability-lte.pdf.

[138] Joona Vehanen, Jyri Hämäläinen, and Markku Pellava. "Handover between LTE and 3G Radio Access Technologies: Test measurement challenges and field environment test planning". Theses. Aalta University, School of Electrical engieering, May 2011. URL: http://lib.tkk.fi/Dipl/2011/urn100472.pdf.

[139] *Universal Mobile Telecommunications System (UMTS); LTE; Access Network Discovery and Selection Function (ANDSF) Management Object (MO)*. ETSI TS 124.312 (ETSI Standard). June 2018.

[140] P. Taaghol, A. K. Salkintzis, and J. Iyer. "Seamless integration of mobile WiMAX in 3GPP networks". In: *IEEE Communications Magazine* 46.10 (Oct. 2008), pp. 74–85. ISSN: 0163-6804. DOI: 10.1109/MCOM.2008.4644122.

[141] W. J. Song et al. "Improvements to seamless vertical handover between mobile WiMAX and 3GPP UTRAN through the evolved packet core". In: *IEEE Communications Magazine* 47.4 (Apr. 2009), pp. 66–73. ISSN: 0163-6804. DOI: 10.1109/MCOM.2009.4907409.

[142] Vivek Gupta. *IEEE P802.21 Tutorial*. Accessed on 2019-08-08. URL: http://www.ieee802.org/21/Tutorials/802%2021-IEEE-Tutorial.ppt.

[143] Lopez Yoann and Robert Eric. "OpenMIH, an Open-Source Media-Independent Handover Implementation and Its Application to Proactive pre-Authentication". In: *Mobile Networks and Management*. Ed. by Kostas Pentikousis et al. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 14–25. ISBN: 978-3-642-11817-3.

[144] Santosh Sheshrao Sambare et al. "Energy Efficient MIH based Independent and Heterogeneous Vertical Handover Algorithm". In: 2018.

[145] J. Jose and A. Prithiviraj. "PMIPV6-HC-MIH: An approach for improving handover performance in NGWN". In: *2012 International Conference on Computing, Electronics and Electrical Technologies (ICCEET)*. Mar. 2012, pp. 910–914. DOI: 10.1109/ICCEET.2012.6203737.

[146] Omar Khattab and Omar Alani. "A Survey on MIH vs. ANDSF: Who Will Lead the Seamless Vertical Handover through Heterogeneous Networks?" In: *International Journal of Future Generation Communication and Networking* 6.4 (Aug. 2013).

[147] ETSI. *3GPP TS 29.275: Universal Mobile Telecommunications System (UMTS);LTE;Proxy Mobile IPv6 (PMIPv6) based Mobility and Tunnelling protocols;Stage 3 (V14.0.0)*. Technical Specifications. Apr. 2017.

[148] R. Wakikawa and S. Gundavelli. *IETF RFC 5844 (May 2010): IPv4 Support for Proxy Mobile IPv6*. Tech. rep. May 2010.

[149] Tony Li et al. *Generic Routing Encapsulation (GRE)*. RFC 2784. Mar. 2000. DOI: 10.17487/RFC2784. URL: https://rfc-editor.org/rfc/rfc2784.txt.

[150] A. Muhanna et al. *IETF RFC 5845 (June 2010): Generic Routing Encapsulation (GRE) Key Option for Proxy Mobile IPv6*. Tech. rep. June 2010.

[151] A. Muhanna et al. *IETF RFC 5846 (June 2010): Binding Revocation for IPv6 Mobility*. Tech. rep. June 2010.

[152] Ed. V. Devarapalli et al. *IETF RFC 5847 (June 2010): Heartbeat Mechanism for Proxy Mobile IPv6*. Tech. rep. June 2010.

[153] ETSI. *3GPP TS 22.186 :5G; Service requirements for enhanced V2X scenarios (3GPP TS 22.186 version 15.3.0 Release 15)*. Tech. rep. July 2018.

[154] ETSI. *Study on enhancement of 3GPP support for 5G V2X services (3GPP TR 22.886 version 15.0.0 Release 15)*. Tech. rep. Sept. 2016.

[155] ETSI. *3GPP TS 22.185 :LTE;Service requirements for V2X services (3GPP TS 22.185 version 14.3.0 Release 14)*. Tech. rep. Mar. 2017.

[156] Alexey Khoryaev. *Evolution of Cellular-V2X Technology use cases,technical challenges and radio-layer solutions for connected cars*. Mar. 2018. URL: https://www.comsoc.org/webinars/evolution-cellular-v2x-c-v2x-technology-use-cases-technical-challenges-and-radio-layer.

[157] ETSI. *Study on LTE support for Vehicle-to-Everything (V2X) services (3GPP TR 22.885 version 14.0.0 Release 14)*. Tech. rep. Dec. 2015.

[158] ETSI. *Study on LTE support for Vehicle-to-Everything (V2X) services (3GPP TR 36.885 version 14.0.0 Release 14)*. Tech. rep. July 2016.

[159] Alessio Filippi et al. *IEEE802.11p ahead of LTE-V2V for safety applications*. May 2016. URL: https://www.nxp.com/docs/en/white-paper/ROADLINK-TECH-WP.pdf.

[160] S. Chen et al. "Vehicle-to-Everything (v2x) Services Supported by LTE-Based Systems and 5G". In: *IEEE Communications Standards Magazine* 1.2 (2017), pp. 70–76. ISSN: 2471-2825. DOI: 10.1109/MCOMSTD.2017.1700015.

[161] Maurice Pope and ETSI. *Universal Mobile Telecommunications System (UMTS);LTE;Architecture enhancements for V2X services(3GPP TS 23.285 version 14.2.0 Release 14)*. Technical Specifications. June 2016.

[162] Dino Flore et al. *Initial Cellular V2X standard completed*. Sept. 2016. URL: http://www.3gpp.org/news-events/3gpp-news/1798-v2x_r14.

[163] K. Savitha and C. Chandrasekar. "Grey Relation Analysis for Vertical Handover Decision Schemes in Heterogeneous Wireless Networks". In: 2011.

[164] Serafim Opricovic and Gwo-Hshiung Tzeng. “Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS”. In: *European Journal of Operational Research* 156.2 (2004), pp. 445–455. ISSN: 0377-2217. DOI: https://doi.org/10.1016/S0377-2217(03)00020-1. URL: http://www.sciencedirect.com/science/article/pii/S0377221703000201.

[165] M. Mouâd and L. Cherkaoui. “A comparison between fuzzy TOPSIS and fuzzy GRA for the vertical handover decision making”. In: *2017 Intelligent Systems and Computer Vision (ISCV)*. Apr. 2017, pp. 1–6. DOI: 10.1109/ISACV.2017.8054983.

[166] Yanmin Zhu, Lei Ni, and Bo Li. “Exploiting mobility patterns for inter-technology handover in mobile environments”. In: *Computer Communications* 36.2 (2013), pp. 203–210. ISSN: 0140-3664. DOI: https://doi.org/10.1016/j.comcom.2012.08.016. URL: http://www.sciencedirect.com/science/article/pii/S0140366412002927.

[167] Walailak Atthirawong and Bart MacCarthy. “An Application of the Analytical Hierarchy Process to International Location Decision-Making”. In: (Aug. 2019).

[168] Prasanta Kumar Dey. “Analytic Hierarchy Process Analyzes Risk of Operating Cross-Country Petroleum Pipelines in India”. In: *Natural Hazards Review* 4.4 (2003), pp. 213–221. DOI: 10.1061/(ASCE)1527-6988(2003)4:4(213). eprint: https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%291527-6988%282003%294%3A4%28213%29. URL: https://ascelibrary.org/doi/abs/10.1061/%28ASCE%291527-6988%282003%294%3A4%28213%29.

[169] Hongcai Sun. “AHP in China”. In: *International Symposium on the AHP (ISAHP)* (2005). URL: http://www.isahp.org/2005Proceedings/Papers/SunHC_ApplicationofANPinChina.pdf.

[170] Qingyang Song and A. Jamalipour. “A network selection mechanism for next generation networks”. In: *IEEE International Conference on Communications, 2005. ICC 2005. 2005.* Vol. 2. May 2005, 1418–1422 Vol. 2. DOI: 10.1109/ICC.2005.1494578.

[171] Jana Krejčí, Ondřej Pavlačka, and Jana Talašová. “A fuzzy extension of Analytic Hierarchy Process based on the constrained fuzzy arithmetic”. In: *Fuzzy Optimization and Decision Making* 16.1 (Mar. 2017), pp. 89–110. DOI: 10.1007/s10700-016-9238-8. URL: https://ideas.repec.org/a/spr/fuzodm/v16y2017i1d10.1007_s10700-016-9241-0.html.

[172] Petra Groselj and Lidija Zadnik Stirn. "Soft consensus model for the group fuzzy AHP decision making". In: 2017. URL: https://www.semanticscholar.org/paper/Soft-consensus-model-for-the-group-fuzzy-AHP-making-Groselj-Stirn/7470c1db5b5ad51154753acf10ff9e1be1e4931b.

[173] Alessio Ishizaka and Philippe Nemery. "Analytic hierarchy process". In: *Multi-Criteria Decision Analysis*. John Wiley and Sons, Ltd, 2013. Chap. 2, pp. 11–58. ISBN: 9781118644898. DOI: 10.1002/9781118644898.ch2. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118644898.ch2. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118644898.ch2.

[174] J. Tu et al. "Performance Analysis of Vertical Handoff in WiFi and WiMAX Heterogeneous Networks". In: *2009 International Symposium on Computer Network and Multimedia Technology*. Jan. 2009, pp. 1–5. DOI: 10.1109/CNMT.2009.5374499.

[175] B. Honman and W. Benjapolakul. "A handover decision procedure for mobile telephone systems using fuzzy logic". In: *IEEE. APCCAS 1998. 1998 IEEE Asia-Pacific Conference on Circuits and Systems. Microelectronics and Integrating Systems. Proceedings (Cat. No.98EX242)*. Nov. 1998, pp. 503–506. DOI: 10.1109/APCCAS.1998.743835.

[176] T. Bouali and S. M. Senouci. "A fuzzy logic-based communication medium selection for QoS preservation in vehicular networks". In: *2016 IEEE International Conference on Communications (ICC)*. May 2016, pp. 1–6. DOI: 10.1109/ICC.2016.7511470.

[177] A. Kaloxylos et al. "An efficient RAT selection mechanism for 5G cellular networks". In: *2014 International Wireless Communications and Mobile Computing Conference (IWCMC)*. Aug. 2014, pp. 942–947. DOI: 10.1109/IWCMC.2014.6906482.

[178] Thiago Coqueiro et al. "A Fuzzy Logic System for Vertical Handover and Maximizing Battery Lifetime in Heterogeneous Wireless Multimedia Networks". In: *Wireless Communications and Mobile Computing* 2019 (Jan. 2019). DOI: 10.1155/2019/1213724. URL: https://doi.org/10.1155/2019/1213724.

[179] Bing Hongyan, He Chen, and Jiang Lingge. "Intelligent signal processing of mobility management for heterogeneous networks". In: *International Conference on Neural Networks and Signal Processing, 2003. Proceedings of the 2003*. Vol. 2. Dec. 2003, 1578–1581 Vol.2. DOI: 10.1109/ICNNSP.2003.1281181.

[180] A. Ezzouhairi, A. Quintero, and S. Pierre. "A fuzzy decision making strategy for vertical handoffs". In: *2008 Canadian Conference on Electrical and Computer Engineering*. May 2008, pp. 000583–000588. DOI: 10.1109/CCECE.2008.4564602.

[181] Tobias Hossfeld et al. "Testing the IQX Hypothesis for Exponential Interdependency between QoS and QoE of Voice Codecs iLBC and G.711". In: 2008.

[182] Charles H. F. dos Santos et al. "Performance evaluation of multiple attribute mobility decision models: A QoE-efficiency perspective". In: *2017 IEEE 13th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)* (2017), pp. 159–166.

[183] Lingfen Sun et al. "VoIP Quality of Experience (QoE)". In: *Guide to Voice and Video over IP: For Fixed and Mobile Networks*. London: Springer London, 2013, pp. 123–162. ISBN: 978-1-4471-4905-7. DOI: 10.1007/978-1-4471-4905-7_6. URL: https://doi.org/10.1007/978-1-4471-4905-7_6.

[184] A Hasswa, Nidal Nasser, and H Hossanein. "Generic vertical handoff decision function for heterogeneous wireless". In: Apr. 2005, pp. 239–243. ISBN: 0-7803-9019-9. DOI: 10.1109/WOCN.2005.1436026.

[185] J. Alcalá-Fdez and J. M. Alonso. "A Survey of Fuzzy Systems Software: Taxonomy, Current Research Trends, and Prospects". In: *IEEE Transactions on Fuzzy Systems* 24.1 (Feb. 2016), pp. 40–56. ISSN: 1063-6706. DOI: 10.1109/TFUZZ.2015.2426212. URL: http://sci2s.ugr.es/fss.

[186] Juan Rada-Vilela. *fuzzylite: a fuzzy logic control library*. 2018. URL: http://www.fuzzylite.com/.

[187] H. Choi et al. "Implementation and Evaluation of Proxy Mobile IPv6 in NS-3 Network Simulator". In: *2010 Proceedings of the 5th International Conference on Ubiquitous Information Technologies and Applications*. Dec. 2010, pp. 1–6. DOI: 10.1109/ICUT.2010.5677817.

[188] ETSI. *3GPP TS 136.213 : LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer Procedures*. Tech. rep. May 2016.

[189] Amine Mohamed Adouane. "Dynamic management of spectral resources in LTE networks". Theses. Université de Versailles-Saint Quentin en Yvelines, Feb. 2015. URL: https://tel.archives-ouvertes.fr/tel-01164507.

[190] A. Masiuk et al. “Resource management method in LTE heterogeneous networks”. In: *2018 14th International Conference on Advanced Trends in Radioelecrtronics, Telecommunications and Computer Engineering (TCSET)*. Feb. 2018, pp. 1131–1134. DOI: 10.1109/TCSET.2018.8336393.

[191] G. Ku and J. M. Walsh. “Resource Allocation and Link Adaptation in LTE and LTE Advanced: A Tutorial”. In: *IEEE Communications Surveys Tutorials* 17.3 (thirdquarter 2015), pp. 1605–1633. ISSN: 1553-877X. DOI: 10.1109/COMST.2014.2383691.

Appendix A

Handover Implementation in NS3

in LTE implementation in NS3, there are two different ways of triggering the handover:

- Manually way (explicitly): This allows to schedule a handover trigger at specific time, by handing over a specific UE to a well known and specified eNB. Thus, it can be achieved by calling the LteHelper::HandoverRequest method:

  ```
  lteHelper->HandoverRequest (time,UEdevice,srcEnBDevice,targetEnbDevice);
  ```

  which will trigger the SendHandoverRequest method on the Radio Resource Control (RRC) entity of the source eNB (LteEnbRrc::SendHandoverRequest)

- Automatic way: This is where a suitable handover algorithm is needed and used. Depending on the situations experienced by the UE, the source eNodeB will automatically trigger handover, according to conditions predefined in the applied handover algorithm.

As illustrated by the figure A.1, the UE must regularly collect measurements that will serve in the handover decision phase. The UE reports these measurements to the source eNodeB RRC instance in appropriate and formatted messages (RrcConnectionReconfiguration) through the RRC Protocol Service Application Provider (SAP). Those measurements have to reach their respective consummers (handover algorithm, automatic neighbour relation) through respective SAP. In the automatic way, the process of the handover decision passes through the following steps[1]:

- Measurement configuration (LteUeRrc::ApplyMeasConfig): Through the AddUeMeasReportConfigForHandover method of the Handover management SAP User, the Handover algorithm ask the RRC entity to configure the measurements reports. Therefore, the RRC takes all these reporting parameters and inform all the future connected UEs to register, collect and send him this measurements.

[1] https://www.nsnam.org/docs/models/html/lte-design.html#overall-design

- Measurement performance (LteUeRrc::DoReportUeMeasurements):
- Measurements reporting triggering (LteUeRrc::MeasurementReportTriggering):
- Measurements reporting (LteUeRrc::SendMeasurementReport):

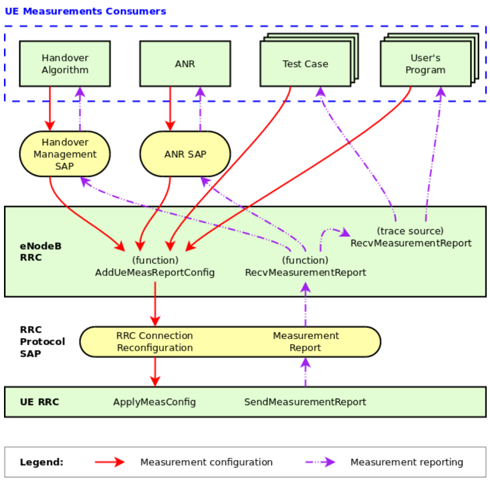


Figure A.1 – Relationship between LTE UE Measurements and its consumers [2]

A.1. Implemented Handover Features in the LTE Module in NS3

In the classical implemented LTE module, the only available handover model is for the horizontal handover in the E-UTRA access radio, which means that it only supports the following features [3]:

- The UE measurement supports only E-UTRA intra-frequency measurements. Therefore, only one measurement object is supposed to be used in the simulation, no need of measurement gaps in order to perform the measurements.
- Event B1 and B2 that are very important for vertical handover are not implemented.

[3] https://www.nsnam.org/docs/models/html/lte-design.html#ue-rrc-measurements-support

- Only reportStrongestCells purpose is supported. Thus, reportCGI and reportStrongestCellsForSON (that are specified in section 5.5 of 3GPP TS 36.331 [134]) are not supported.

- S-Measure is not yet supported.

- Carrier aggregation is supported, however Event A6 is not implemented.

- Speed dependent scaling of time-to-trigger (section 5.5.6.2 of the standard TS36.331 [134]) is not supported

- In summary, only X2-based handover (Intra-LTE handover) was implemented in LTE module

- For decision parameter, one criterion is considered: whether RSRQ (in A2A4RsrqHandoverAlgorithm), RSRP (in A3RsrpHandoverAlgorithm), distance between UE and cell in automatic attachment way, during the search selection step (by calling LteHelper::Attach which trigger AttachToClosestCell in LteHelper). Note that the RSRP and RSRQ are reported in term of range (0 -97 for RSRP and 0-34 for RSRQ) as specified in 3GPP TS 36.133 [136]. RSRP Measurement Report Mapping and RSRQ Measurement Report Mapping can be found respectively in section 9.1.4 and 9.1.7 of this standard [136]. The conversion from RSRP or RSRQ values to their respective range is implemented in LteCommon, using the following formulas:
  RSRP value to range:

  $$Dbm2RsrpRange = Min(Max(floor(Rsrp + 141), 0), 97) \tag{A.1}$$

  Range to RSRP value :

  $$RsrpRange2Dbm = range - 141 \tag{A.2}$$

  RSRQ value to range:

  $$Db2RsrqRange = Min(Max(floor(Rsrq * 2 + 40), 0), 34) \tag{A.3}$$

  Range to RSRQ value :

  $$RsrqRange2Db = (range - 40)/2 \tag{A.4}$$

This conversion in range and the range-decision-based also redirect us to the importance of using fuzzy logic for dealing with such values.

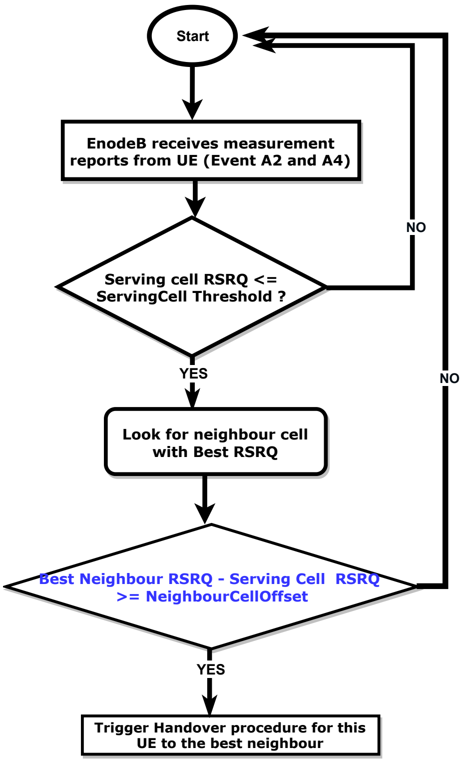


Figure A.2 – Procedure for the RSRQ-based handover algorithm in LTE: A2A4RsrqHandoverAlgorithm

4

The procedure taken by A2A4RsrqHandoverAlgorithm is illustrated by the figure A.2. This algorithm is based on A2 (serving cell's RSRQ becomes worse than threshold) and A4 (neighbour cell's RSRQ becomes better than threshold) event measurement report. A2 event means that the UE is experiencing poor signal quality and may benefit from a handover. However, A4 is for detecting neighbouring cells and acquiring their corresponding RSRQ from every attached UE, which are then stored internally by the algorithm. The value of these two thresholds are of great importance (default values are: 30 for A2 ServingCellThreshold and 0 for A4 NeighbourCellOffset).

The A3RsrpHandoverAlgorithm is based on the RSRP and tends to hand the UE over to the strongest available cell in its neighbouring. We illustrate its procedure by the figure A.3. It is to be noticed that the two variables (hysteresis, time-to-trigger) were introduced in order to mitigate the ping-pong effects that frequently affect that kind of handover algorithm. A3 offset range is starting from -15 to 15.

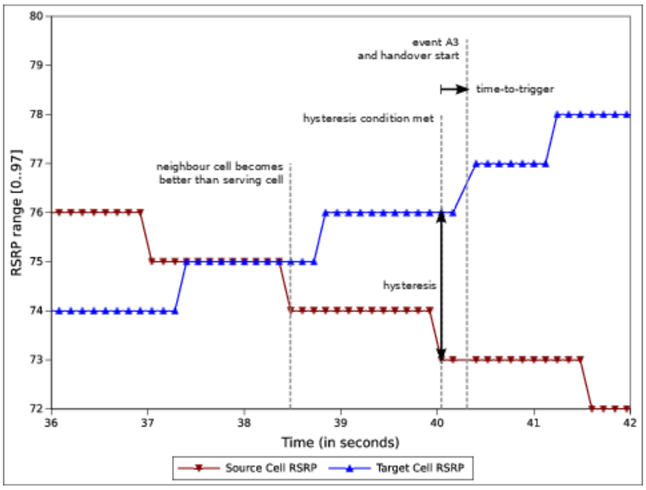


Figure A.3 – Procedure for the RSRP-based handover algorithm in LTE : A3RsrpHandoverAlgorithm

[5]

A.2. Added Implemented Features for Vertical Handover Support in the LTE Module

- In LteRrcSap: implementation of:
  - THRESHOLD-RSSI in ThresholdEutra struct
  - EVENT-B1 in ReportConfigEutra struct EVENT-B2
  - RSSI triggerQuantity
  - struct RatMeasResultEutra (Add of other measurements parameters: RSSI, bandwidth, QoE, Speed, etc)
  - struct RatMeasResults (struct to support these new parameters in measurements report)
- In LteUeRrc: Implementation of :
  - Measurement report configuration
- In LteEnbRrc: Implementation of :
  - Measurement report configuration
- In PointToPointEpc6Pmipv6Helper: Implementation of :

  - S1-U, S5, X2 parameters configuration method, for the purpose of performance metrics analysis

- In A2A4RsrqHandoverAlgorithm: Implementation of :
  - B1, B2 MeasId
- In YansWifiPhy: Implementation of:
  - Attributes: UeMeasurementsFilterPeriod, RssiSinrSamplePeriod
  - tracesources: ReportUeMeasurements, ReportCurrentCellRssiSinr
  - Methods: ReceiveAndStoreRssi (fromAddress,RSSI)
- In Ipv6L3Protocol: Implementation of:
  - Methods : FindUpInterface (), IsUseMivh (), IsUseFuzzy(), Set|GetMivhFuzzyDeviceIndex(), SetUseMivh|Fuzzy(), Setup|ClearTunnelAndRouting ();
  - Respective variables and parameters for those methods.
- In Ipv6MobilityHeader:
  - Adding of 802.11P, LTE RAT type in the enumeration

A.2.1. Integration of Fuzzylite library in NS3

Fuzzylite is a free and open-source fuzzy logic control library programmed in C++ for multiple platforms (e.g., Windows, Linux, Mac, iOS). It is also implemented in other programming language such as Java and Android as jfuzzylite. A Qt version is commercially available. To do this integration, we firstly compiled and installed the fuzzylite library. Then, we included the fuzzylite path and its dependencies in our project. We processed as follows:

- we included the fuzzylite path to the *INCLUDE_PATH* in the wscript of the project in NS3.
- we added the path of the fuzzylite binary files (fuzzylite.so) in the wscript of the project in NS3 and we also exported it in *LIBRARY_PATH*.
- We had to add the fuzzylite to the linker in the wscript

After that, we have to include the library in ld.so.conf by adding the fuzzylite library path to the */etc/ld.so.conf* as root, then issuing the command: *$ sudo ldconfig*.

The resulting wscript might look like:

```
obj = bld.create_ns3_program ('program-name', ['dependent-NS3-Modules'])
obj.source = 'program-name-source.cc'
obj.includes = ['path/to/include/directory','path/to/fuzzylite/directory']
obj.lib = ['fuzzylite']
obj.libpath = ['path/to/fuzzylite/directory/release/bin']
...
```

Therefore, we can use the fuzzy library in our project by inserting

```
#include <fl/Headers.h>
```

However, for the program files located in the scratch directory of NS3, a workaround was needed in order to handle them. For that, a modification need to be made in the WAF main wscript located in the top directory of NS3, specifically in the

```
add_scratch_programs(bld)
```

As a workaround, we decided to include the term *fuzzy* in the name of each program using fuzzy logic while located in the scratch directory. Then, we used the *filename.find("fuzzy")!=-1* search method, to configure the fuzzy library and the "includes" commands required by these programs. The code of *add_scratch_programs(bld)* method in the main wscript becomes:

```
 ...
for filename in os.listdir("scratch"):
if filename.startswith('.') or filename == 'CVS':
continue
if os.path.isdir(os.path.join("scratch", filename)):
obj = bld.create_ns3_program(filename, all_modules)
obj.path = obj.path.find_dir('scratch').find_dir(filename)
obj.source = obj.path.ant_glob('*.cc')
obj.target = filename
obj.name = obj.target
obj.install_path = None
elif filename.find("fuzzy")!=-1:
name = filename[:-len(".cc")]
obj = bld.create_ns3_program(name, all_modules)
obj.path = obj.path.find_dir('scratch')
obj.source = filename
obj.includes = ['path/to/include/directory','path/to/fuzzylite/directory']
obj.lib = ['fuzzylite']
obj.libpath = ['path/to/fuzzylite/directory/release/bin']
obj.target = name
obj.name = obj.target
obj.install_path = None
elif filename.endswith(".cc"):
name = filename[:-len(".cc")]
obj = bld.create_ns3_program(name, all_modules)
obj.path = obj.path.find_dir('scratch')
```

```
obj.source = filename
obj.target = name
obj.name = obj.target
obj.install_path = None
...
```

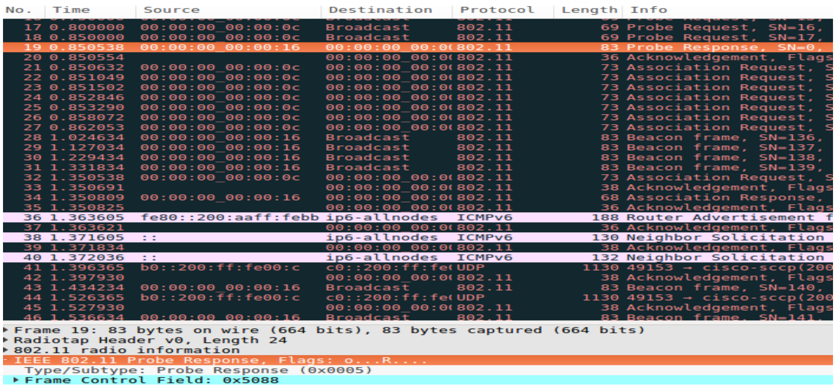
A.2.2. Implementation of Data Gathering and Measurement Methods in NS3

In order to have the parameters value that are needed to be used in the vertical handover decision phase, we implemented the following methods, in addition to what was available in the LTE module.

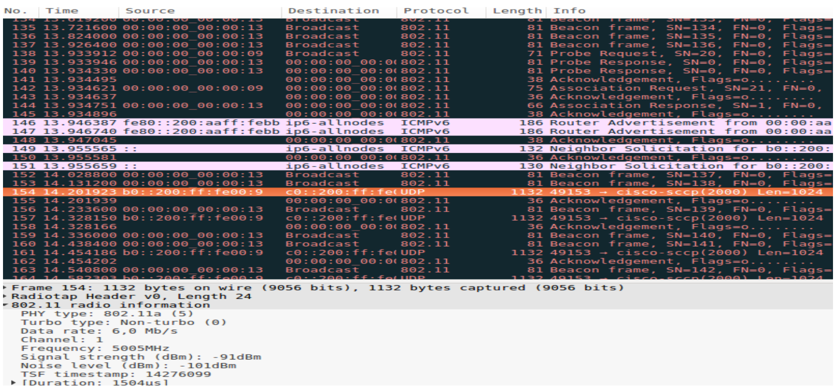
- In YansWifiPhy: *bool IsUseMivh () const; bool IsMeasMonitor() const, void SetUseMivh (bool useMivh), void SetMeasMonitor (bool measMonitor), bool IsForWave () const, void SetForWave (bool forWave)* with their corresponding parameters;
- Measurement storage file and measurement saving in *YansWifiPhy::EndReceive* methods;
- Parameterization and configuration during the installation methods : *InstallWifi, InstallWave, YansWifiPhy constructor*;
- For LTE, measurement are done by the UE PHY layer, and reported by the UE RRC instance to the eNB RRC instance. Measurement are then retrieved in the *ReportUeMeasurement* callback.

Appendix B
Implementation validation

The following figures illustrated the implementation validation steps through screenshots from PCAP dumping with wireshark software .



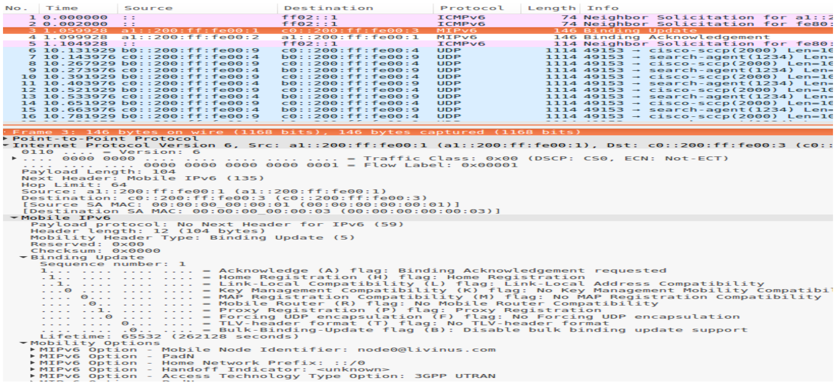
(a)



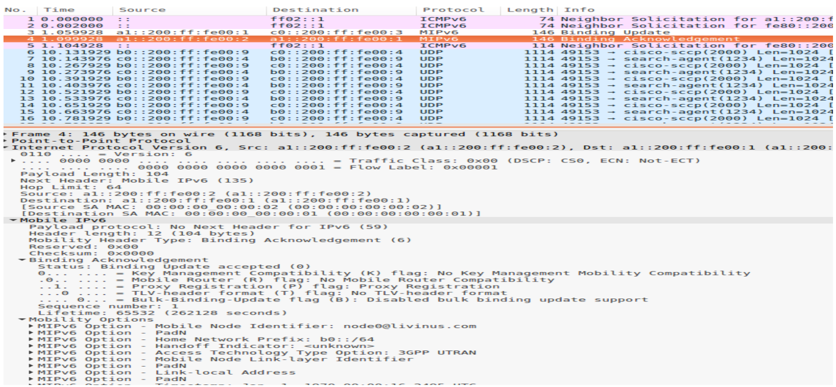
(b)

Figure B.1 – (a) PMIP: UE first connection details. (b) PMIP:Wifi MAG2 connection details (with RSSI and Noise signal) .

Figure B.1 shows the validation of the first function which is the MN attachment detection. Indeed, reader can see that the MN sends probe request and then the MAG responds with probe response. This is the beginning of PMIPv6-based protocol execution.



(a)



(b)

Figure B.2 – (a) PMIP: PBU message details:Flag P is On, without HNP, 3GPP. (b) PMIP:LTE Handover details with HNP assigned.

Figure B.2 illustrates the binding and registration function. In figure B.2a, we illustrate the Proxy Binding Update (PBU) message that the MAG sends to the LMA (in Centralized architecture) or the MAAR (Mobile Anchor and Access Router in DMM, referred as a MAG in the following section instead of LMA when talking about DMM scenario). We can see that the P flag is on and that the message does not contain any HNP. This means that the LMA or MAAR will need to assign a HNP which will be advertised to the MN. The RAT is also available showing that we entered a LTE coverage zone. In figure B.2b, the PBA message details is shown. Notice that it contains a new assigned HNP. From that, we can also deduce that it takes around 0.04 seconds to the LMA from receiving PBU to sending PBA. This also depends on the number of entries available in the BCE and how the BCE is implemented. Reason why the hash function[1] is considered in our PMIP-MIVH.

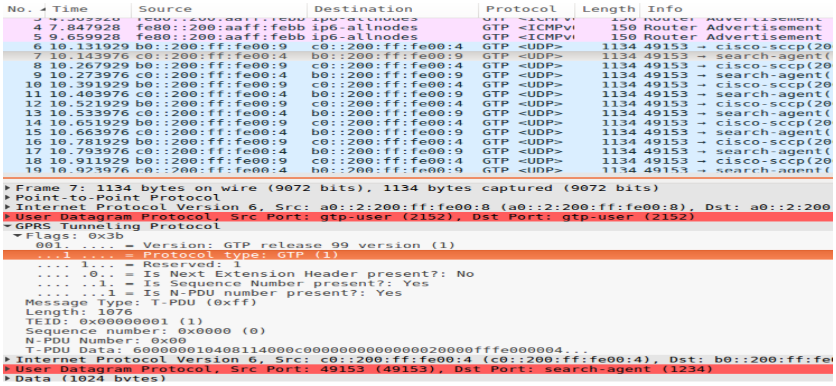


Figure B.3 – PMIP:Tunnel creation between MAGs and LMA

Figure B.3 illustrates how the tunnel between PMIP entities (MAGs and LMA) is established. It highlights that a GPRS Tunneling Protocol (GTP) tunnel is established between the LMA (a0::2:200:ff:fe00:8) and the MAG (a0::2:200:ff:fe00:7) in order to transmit a UDP data packet from the CN (c0::200:ff:fe00:4) to the MN (b0::200:ff:fe00:9).

[1] http://www.partow.net/programming/hashfunctions/index.html

Collecte des données Véhicule/Environnement et remontée avec réseau Cellulaire et réseau Véhiculaire

Le transfert vertical intercellulaire est l'une des technologies clés qui facilitera le déploiement de véhicules connectés et autonomes. Aujourd'hui, l'émergence des réseaux véhiculaires : les communications de véhicule à véhicule (V2V), véhicule à infrastructure (V2I) et de véhicule à tout (V2X) a permis de nouvelles applications telles que les Systèmes de Transport Intelligents Coopératifs (C-ITS), les applications temps réel (par exemple, la conduite autonome), applications de gestion du trafic routier et applications de confort. Cependant, ces réseaux se caractérisent par une grande mobilité et de fréquents changements de la topologie, ce qui génère des réseaux épars et nécessitant des mécanismes de transfert pour le maintien de la continuité de session.

Pour résoudre ce problème, nous avons proposé le PMIP-MIVH, une approche basée sur le PMIP et qui profite des avantages de l'utilisation d'une interface logique dans le traitement du transfert vertical intercellulaire. Pour améliorer et étendre notre approche, une méthode multicouche de sélection du meilleur réseau disponible, basée sur la logique floue a également été proposée. Les résultats analytiques et les résultats des simulations montrent tous que les solutions proposées sont performantes comparées aux autres méthodes de transfert existantes et améliorent efficacement la gestion de la mobilité dans les réseaux véhiculaires.

Réseaux Véhiculaires, Transfert Intercellulaire Vertical, PMIPv6, Gestion Distribuée de Mobilité, Réseaux Cellulaires, MIVH, C-V2X

Data Collection Vehicle/Environment and Ascent with Cellular and Vehicular Networks

Vertical handover is one of the key technologies that will facilitate the connected and autonomous vehicles deployment. Today, the emergence of Vehicular Ad hoc Networks (VANETs): Vehicle-to-Vehicle (V2V) communications, Vehicle-to-Infrastructure (V2I) and Vehicle-to-Everything (V2X) has enabled new applications such as Cooperative Intelligent Transport Systems (C-ITS), real-time applications (for example, autonomous driving), road traffic management applications and comfort applications. However, these networks are characterized by a high level of mobility and dynamic change in the topology, which generates scattered networks and requires handover mechanisms for maintaining ongoing session continuity.

To address this problem, we have proposed a PMIP-based Mobile Internal Vertical Handover (PMIP-MIVH) approach which takes advantage of the use of a logical interface in handling handover. To improve and extend our approach, a cross-layer and fuzzy logic-based selection method of the best available network has been also proposed. Analytical results and conducted simulation results all show that the proposed solutions overperform the existing handovers and enhance efficiently the handover management in the VANETs field.

VANETs, Vertical Handover, PMIPv6, Distributed Mobility Management, Cellular Networks, MIVH, C-V2X

Discipline : INFORMATIQUE

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Université de Reims Champagne-Ardenne

CRESTIC - EA 3804

BP 1039-51687 Reims CEDEX 2