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Equipes d'accueil : Orange Labs CMA/MAX (ex. CMA/BATS) - IRISA/DIONYSOS
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Cooperation and Self-* for Small Cells Networks

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"A father's goodness is higher than the mountain, a mother's goodness deeper than the sea."

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Abstract

The recent phenomenal traffic growth is driving mobile operators to tier their pricing plans based on consumed bandwidth. To maximize data traffic monetization, operators will need to consider smarter approaches while upgrading their current networks or deploying new ones. Small Cells are an integral part of both mature 3G/4G and future 5G cellular networks. Small Cells may be de facto deployed in heterogeneous architectures for Macro cells densification, or homogeneously for minimum broadband coverage. In this respect, emerging challenges must be tackled: a reliable and economical backhaul is vital for Small Cells deployments. It is specifically more constraining for Small Cells deployments in green-field areas, where transport infrastructure are absent or non-owned. In other words, the mobile operator wants to ensure good quality access to broadband services based only on Small Cells, while reducing overall installation cost. In this thesis, we focus on cost-efficient backhaul solutions that may provide the minimum capacities required by end users.

Our first contribution targets the provisioning of 4G Small Cells networks with sufficient capacity. Firstly, we provide a cost-efficient method that minimizes backhaul cost while respecting the constraints of access network traffic demand and connecting technologies characteristics. This method provides with customized cost-optimal backhaul solutions for a given Small Cells access network; those solutions are made up of different linking technologies. Secondly, we analyze the impact of end users activity -i.e. data exchange- on generated traffic on both a Small Cell logical interfaces S1 and X2; by taking into account different traffic components of an end user device. The analysis supplies with valuable insights on selecting the needed backhaul solutions.

In our second contribution, we focus on improving capacity in WLAN systems. We design a MAC scheduling scheme for uplink multi-users transmissions: it enables to exchange minimal control frames required for the establishment of transmissions between the multiple transmitters and the receiver. Both analytic results and conducted proof-of-concept simulations show improved efficiency for both system and user oriented performances.

Keywords: Small Cells, Green-Field Deployments, Wireless Backhaul, WLAN High capacity, UL MU-MIMO.

Résumé

La croissance phénoménale du trafic pousse les opérateurs mobiles à différencier leurs plans de tarification en se basant sur la bande passante consommée. Afin de maximiser la monétisation du trafic de données, les opérateurs devront envisager des approches plus intelligentes tout en améliorant leurs réseaux actuels ou en déployant de nouvelles infrastructures. Les Small Cells sont une partie intégrante des réseaux cellulaires matures 3G/4G et futurs 5G. Les Small Cells peuvent être de facto déployées dans des architectures hétérogènes pour la densification des réseaux macrocellulaires, ou de façon homogène pour une couverture en haut débit. Pour le deuxième case de déploiement, de nouveaux défis doivent être résolus: un réseau de collecte fiable et économique est vital pour les déploiements des Small Cells. Le réseau de collecte est spécifiquement plus contraignant pour les déploiements des Small Cells dans les zones dites *green-field*, où les infrastructures de transport sont absentes ou présentes mais ne peuvent être contrôlées par l'opérateur. En d'autres termes, l'opérateur mobile souhaite garantir une bonne qualité d'accès aux services haut débit en se basant uniquement sur des Small Cells, tout en réduisant le coût global de l'installation. Dans cette thèse, nous nous focalisons sur des solutions de réseau de collecte rentables qui peuvent fournir les capacités minimales requises par les utilisateurs finaux.

Notre première contribution vise à assurer une capacité suffisante aux réseaux Small Cells 4G. Tout d'abord, nous proposons une méthode rentable qui minimise les coûts du réseau de collecte tout en respectant les contraintes de : 1) demande de trafic dans le réseau d'accès, et de 2) caractéristiques technologiques des liens de collecte. Cette méthode permet d'obtenir des solutions sur mesure de réseau de collecte à coûts optimal pour un réseau d'accès donné, basé sur des Small Cells; ces solutions sont constituées de différentes technologies de liaison. Deuxièmement, nous analysons l'impact de l'activité des utilisateurs finaux sur le trafic généré à la fois sur les deux interfaces logiques S1 et X2 d'une Small Cell, tout en tenant compte les différentes composantes de trafic moyen d'un utilisateur final. Cette analyse permet d'avoir un aperçu très utile pour la sélection des solutions nécessaires au réseau de collecte.

Dans notre deuxième contribution, nous nous focalisons sur l'amélioration des capacités des systèmes WLAN. Nous concevons un protocole d'ordonnancement MAC pour les transmissions uplink multi-utilisateurs: il permet un échange minimal des trames de contrôle requises pour la mise en place des transmissions entre les multiples émetteurs et le récepteur. Les résultats d'analyse et de simulations révèlent des performances améliorées, d'un point de vue du système et de l'utilisateur.

Mots-clefs: Small Cells, Dépoilements Green-Field, Réseau de Collecte Sans Fil, WLAN Haute capacité, UL MU-MIMO.

Résumé Français

0.1 Introduction

Les small cells ont vu le jour dans le contexte de la densification des réseaux, principalement dans les zones urbaines. En fait, une estimation récente indique que le trafic de données mobiles a augmenté de 74%[1] durant l'année 2015 et prévoit une augmentation annuelle de 53%[2] de 2015 à 2020. Cette demande accrue est due à différents facteurs. Premièrement, les équipements sans fil sophistiqués des utilisateurs finaux sont améliorés en permanence pour prendre en charge de nouvelles fonctionnalités. Deuxièmement, des applications gourmandes en bande passante avec des contenus riches se développent constamment. En troisième lieu, le revenu moyen par utilisateur croit à des vitesses différentes selon les zones géographiques; cela favorise une grande pénétration des smartphones.

Dans ce contexte, les opérateurs de réseaux mobiles devront fournir plus de capacités afin d'assurer à leurs abonnés les vitesses qu'ils exigent. La densification du réseau sert à cet effet. La technologie des small cells est l'un des principaux moyens qui permettent d'améliorer la capacité dans un réseau. Les small cells sont utilisées conjointement avec des macrocellules pour fournir la couverture/capacité, avec la possibilité de handoff entre les deux technologies. Les small cells sont des solutions avantageuses quant à l'accroissement de la capacité du réseau, elles peuvent également servir de camouflage pour les 'trous' de couverture des macrocellules; tout cela grâce à leur transposition en version miniaturée des macrocellules.

En effet, le terme générique "Small Cells" désigne *les noeuds d'accès radio à faible puissance, contrôlés par l'opérateur, y compris les noeuds opérant dans un spectre*

[1]Source: Cisco VNI Mobile, 2016
[2]Source: Cisco VNI Mobile, 2016

sous licence et la Wi-Fi sans licence [3]. En la comparant à une macrocellule typique dont la couverture peut atteindre quelques dizaines de kilomètres, la couverture d'une small cell varie entre des dizaines à quelques milliers de mètres. Typiquement, une Femtocell peut émettre un signal radio à une puissance maximale de 23dBm; ce signal peut atteindre jusqu'à 50m de portée. La puissance de transmission d'une Picocell varie entre 23 et 30dBm, son rayon de couverture est compris entre 200-300m. Une Microcell a une portée de couverture plus importante: jusqu'à 2km; elle a une puissance de transmission de 30-46dBm. La portée d'un point d'accès Wi-Fi dépend de la technologie, mais ne dépasse pas 250m. Il transmet les signaux sans fil aux alentours de 25dBm.

La compacité des small cells a plusieurs avantages. Tout d'abord, les small cells permettent d'assurer une couverture meilleure. Les Microcells sont basiquement conçues pour étendre la couverture au profit des utilisateurs indoor/outdoor, là où la couverture d'une macrocellule est insuffisante. En outre, les Femtocells déployées conjointement avec des macrocellules permettent d'améliorer la couverture, particulièrement dans les déploiements moins denses. En fait, l'opérateur mobile japonais Softbank a réussi à déployer des Femtocells pour couvrir des villages et des localités isolées, et ce en utilisant une ingénierie spécifique à l'outdoor. Les small cells ont besoin de moins de puissance : puisque les small cells utilisent des stations de base plus petites, elles nécessitent moins de ressources énergétiques, que cela soit pour la transmission du signal radio ou la consommation de l'équipement. Les déploiements denses des small cells promettent de réduire significativement la consommation d'énergie. Lorsque les small cells sont utilisées en mode veille, l'impact sur l'efficacité énérgitique du réseau d'accès radio (RAN) est proéminent. Les small cells génèrent moins de coûts. En effet, les besoins énergétiques faibles sont traduits automatiquement par des économies de coûts. De plus, les équipements de small cells coûtent beaucoup moins cher, ce qui permet de réaliser d'importantes économies. Finalement, les small cells sont faciles à déployer, puisqu'elles sont commercialisées dans des boitiers de taille moyenne à petite, et qu'elles n'occupent pas beaucoup d'espace.

0.2 Problématique de la thèse

Les avantages potentiels qu'offrent les small cells ont poussé certains opérateurs de réseaux mobiles à les considérer comme alternative de couverture dans les zones où

[3] Source: Small Cell Forum

l'opérateur ne possède ou ne peut contrôler les infrastructures de transport. En effet, les small cells peuvent être déployées seules dans des régions où aucune infrastructure d'accès n'est accessible pour assurer une connectivité au haut débit de l'opérateur. Cependant, le coût du déploiement de nouvelles infrastructures de transport est élevé comparé aux revenus de la population. D'un point de vue économique, il n'est plus avantageux de servir ce genre de populations. Le *business plan* du réseau de collecte ne doit pas être un obstacle au déploiement des small cells dans ces zones.

Dans ce contexte, les technologies sans fil (comme micro-ondes, satellite ou Wi-Fi) sont des solutions stratégiques pour réduire les coûts des réseaux de transport et ainsi, faciliter le déploiement des small cells. Comparées aux technologies filaires (comme la fibre ou le câble coaxial), les infrastructures sans fil du réseau de collecte ont quelques limitations : l'une des plus cruciales est un faible débit. Le réseau de collecte des small cells doit être en mesure de transporter le trafic des utilisateurs finaux sans sacrifier les performances du réseau.

Dans cette thèse, nous abordons les défis des réseaux de collecte sans fil des small cells, destinées à couvrir des zones où aucune infrastructure filaire de l'opérateur n'est disponible. Pour cela, nous visons à satisfaire les besoins des zones de service en termes de capacité, tout en gardant à l'esprit les règles de déploiement et les contraintes économiques de l'opérateur.

0.3 Contributions de la thèse

Le déploiement des small cells dans les zones non-couvertes est fortement associé à la fourniture de services internet avec une qualité de service minimale, tout en générant des coûts plus faibles et moins de complexité de dépoilements. Même si les small cells sont des solutions à faible coût et faciles à déployer, leur réseau de collecte doit également être rentable tout en assurant une connectivité de bonne qualité. Le choix des solutions de collecte les plus adaptées est dicté par les exigences des utilisateurs finaux en termes de débit, dans le temps et l'espace. Le réseau de collecte peut être composé de différentes solutions pour le même RAN: le Wi-Fi est une solution prometteuse, spécialement pour les small cells des WLAN. Le Wi-Fi permettrait d'atteindre de grandes capacités lorsque certaines technologies évoluées y sont incluses: la technique uplink multi-utilisateurs MIMO (UL MU-MIMO) est un facteur clé pour l'amélioration des capacités des systèmes WLAN et des utilisateurs en uplink.

Cette thèse est composée de deux parties. Dans la première partie, nous analysons les caractéristiques du réseau de collecte des small cells, ensuite nous proposons deux approches pour améliorer le dimensionnement de la collecte par rapport à la demande de trafic des utilisateurs finaux.

La première approche vise à choisir des solutions de collecte tout en respectant certaines contraintes:

- **Planification optimale des réseaux small cells en fonction du coût dans les zones sans infrastructures** : nous ciblons le problème du choix des solutions de collecte les plus appropriées, y compris les types de technologies et les nœuds agrégateurs, qui génèrent le coût d'installation le plus minimaliste. Nous considérons un ensemble de small cells destinées à desservir une zone spécifique. Les emplacements des small cells sont prédéfinis par la planification radio. Nous proposons ensuite un modèle d'optimisation de coût exprimé sous forme d'un problème d'optimisation. Ce problème vise à minimiser le coût des connexions de collecte tout en respectant les contraintes des caractéristiques des technologies et du trafic du réseau. Un accès réseau small cells peut être relié de différentes façons selon les technologies définies par la stratégie de l'opérateur, et peut donc avoir différentes solutions de collecte.

Dans un deuxième temps, nous évaluons l'impact de l'activité des équipements d'utilisateurs finaux sur le trafic acheminé par les interfaces logiques d'une small cell:

- **Planification de réseaux small cells basée sur une analyse de trafic** : le besoin en débit d'une zone de service indique la capacité des technologies de collecte sélectionnées. En fait, ce besoin devrait être quantifié afin de pouvoir déployer les small cells d'une manière efficace et scalable. Cette quantification permettrait d'évaluer la quantité de trafic acheminée depuis le réseau coeur à l'utilisateur final via la small cell en accès, et vice versa. Pour cette raison, nous analysons le trafic acheminé par un segment de collecte des small cells. En effet, nous divisons la *pipeline* de la collecte en plusieurs composantes selon deux critères : 1) leur acheminement via l'interface S1 ou X2, et 2) le type d'information qu'elles acheminent: paquets de signalisation ou de données d'utilisateurs. En utilisant les mêmes critères, nous partageons le débit moyen d'un utilisateur en différents pourcentages de participation. Nous modélisons ainsi le comportement du trafic généré sur les deux interfaces logiques (S1 et X2) d'une small cell en utilisant une chaîne de Markov. Ce modèle prend en considération l'effet qu'a l'activité des utilisateurs finaux sur les interfaces de connexion de la small cell.

La deuxième partie de cette thèse est dédiée à la conception, l'évaluation analytique et la mise en œuvre d'un protocole d'ordonnancement des transmissions UL MU-MIMO en WLAN.

- **Amélioration de la capacité des systèmes Uplink multi-utilisateurs MIMO** : en tant que solution de collecte sans fil très attractive pour tout type de technologie small cell (qu'elle soit cellulaire ou basée sur dans les WLAN), les liens Wi-Fi devront supporter des performances symétriques ulpink/downlink en débit. Des techniques supplémentaires, comme les transmissions multi-utilisateurs, peuvent être incluses dans les systèmes WLAN afin d'atteindre la capacité souhaitée. Dans cette perspective, nous identifions et analysons les problèmes techniques de multi-utilisateurs MIMO en uplink. Nous proposons ensuite un nouveau protocole d'ordonnancement de la couche MAC dont le but est de réduire les messages de contrôle générés par les multiples émetteurs et le récepteur afin d'établir cette transmission. Nous établissons deux versions de ce protocole: basique et améliorée. Par la suite, nous modélisons la version basique en utilisant un modèle semi-Markov afin d'évaluer les performances du système. Enfin, nous effectuons plusieurs simulations pour vérifier la haute efficacité apportée par le protocole uplink MU-MIMO.

0.4 Conclusion

Dans cette thèse, nous avons traité les problématiques d'accès aux services haut débit en se basant uniquement sur des small cells, dans des zones sans infrastructures de l'opérateur. Plus précisément, nous avons effectué une analyse, modélisations et optimisation des réseaux d'accès et de collecte des small cells. Le but est d'assurer l'accès aux services haut débit avec une qualité de service satisfaisante tout en gardant à l'esprit l'aspect crucial des coûts encourus par les déploiements des small cells. Initialement, nous avons détaillé le contexte général de ce travail, à savoir les réseaux small cells; ensuite nous avons abordé les problématiques suivantes.

Premièrement, nous avons considéré un réseau d'accès entièrement couvert par small cells. Ce RAN a au moins un accès à un noeud agrégateur de service appartenant à l'opérateur. Nous avons proposé un modèle qui minimise les coûts engagés dans le réseau de collecte tout en respectant trois contraintes principales : les capacités des liens, la portée de la technologie utilisée et l'unicité du noeud agrégateur. Les résultats de calcul ont confirmé que les technologies sans fil sont plus rentables que les filaires. Ces résultats ont permis aussi d'obtenir des solutions hybrides pour un réseau de collecte sans fil.

Ensuite, nous avons effectué une analyse pour évaluer l'influence de l'activité des UEs sur le trafic des connexions logiques d'une small cell. En fait, les solutions sans fil utilisées dans le réseau de collecte dépendent des besoins de la zone à servir en termes de trafic; celui-ci est directement lié à la quantité de données échangées entre les équipements des utilisateurs finaux et le réseau de l'opérateur. Nous avons fournis également une classification du trafic d'un UE selon l'interface logique par laquelle il est acheminé (S1 ou X2) ou son type (plan de contrôle ou de données).

Enfin, nous nous sommes concentrés sur l'amélioration de la capacité des systèmes WLAN en uplink. Les techniques uplink MU-MIMO ne sont pas encore normalisées par aucun organisme de normalisation WLAN, bien qu'elles soient des alternatives propices à l'amélioration de la capacité. Nous avons proposé un protocole MAC qui permet d'ordonnancer une transmission uplink MU-MIMO tout en restant rétro-compatible avec les normes IEEE 802.11 actuelles; i.e. échanger le moins de trames de contrôle entre les multiples émetteurs et le récepteur. Nous avons évalué la performance système de ce protocole en utilisant un modèle semi-Markovien. Finalement, nous avons proposé une version améliorée qui permet de réduire d'avantages les overheads, et avons vérifié ensuite l'efficacité des deux versions par des simulations.

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Abbreviations

A

AAA	Authentication, Authorization, and Accounting
ACK	Acknowledgment
aGW	Aggregation Gateway
AP	Access Point

B

BO	Backoff
BS	Base Station
BSS	Basic Service Set

C

CAPEX	Capital Expenditure
CDF	Cumulative Distribution Function
CN	Core Network
CoMP	Coordinated Multipoint
CTS	Clear To Send

D

DCF	Distributed Coordination Function
DL	Downlink
DIFS	DCF Inter-Frame Space
DoS	Denial of Service
DTV	Digital TV

E

EAP	Extensible Authentication Protocol
eICIC	enhanced Inter-cell interference coordination

EIFS	Extended Inter-Frame Space
EPC	Evolved Packet Core
H	
HOL	Head Of Line
G	
GNSS	Global Navigation Satellite Systems
GPRS	General Packet Radio Service
GTP	GPRS Tunnelling Protocol
L	
LOS	Line-of-Sight
M	
MAC	Media Access Control
MC	Macro Cell
MIP	Mobile IP
MME	Mobility Management Entity
mmWave	Millimeter Wave
MPR	Multi-Packet Reception
MU	Multi-Users
MW	Microwave
N	
nLOS	Near Line-of-Sight
NLOS	Non Line-of-Sight
NTP	Network Time Protocol
P	
PHY	Physical
PMIP	Proxy Mobile IPv6
PoC	Point of Concentration
PoP	Point of Presence
ppb	parts per billion
PS	Packet Switched
PtMP	Point-to-Multipoint
PtP	Point-to-Point

Q

QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
QPEX	Operating Expenditure

R

RAN	Radio Access Network
RTS	Request To Send
RTT	Round Trip Time

S

SC	Small Cell
SCF	Small Cell Forum
SC-GW	Small Cell Gateway
SCTP	Stream Control Transmission Protocol
S-GW	Serving Gateway
SIFS	Short Inter-Frame Space
SIPTO	Selective IP Traffic Offload
STA	Station
SU	Single-User
SyncE	Synchronous Ethernet

T

TCO	Total Cost of Ownership
TDD	Time Division Duplex
TGax	Task Group ax
TV	Television
TVWS	TV White Space
TXOP	Transmission Opportunity

U

UDP	User Datagram Protocol
UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink

W

VHF	Very High Frequency

W

WP2AA	Wait-to-Pick-As-Available
WP2AA-E	Wait-to-Pick-As-Available Enhanced
WAG	WLAN Access Gateway
WLAN	Wireless Local Area Network

Introduction

The early days of Small Cells Networks

The *raison d'etre* of small cells is to propose new alternatives to network densification, predominantly in urban areas. Actually, one recent estimation states that global mobile data traffic grew 74%[4] in 2015 and is foretasted to grow annually at a rate of 53%[5] from 2015 to 2020. This ever growing thirst for mobile/wireless data is triggered by different elements. First, sophisticated wireless end users devices are constantly developed to support new features. Second, bandwidth-hungry applications with rich contents are continuously proliferating. Third, Average Revenue Per User (ARPU) is growing, although at different paces depending on world regions; this is favoring high smartphone penetration.

In this context, Mobile Networks Operators (MNOs) need to add more capacity to continue providing their subscribers with the speeds they demand. This is what network densification is meant for. Small cells are one of the key ways to improve system capacity. Small cells are employed together with macrocells to provide coverage/capacity with eventual handoff capabilities. Small cells are attractive solutions towards increasing the network capacity and even fitting macrocells coverage 'holes', thanks to their "smaller" reincarnation of macrocells.

As a matter of fact, the umbrella term "Small Cells" refers to *operator-controlled, low-powered radio access nodes, including those that operate in licensed spectrum and unlicensed carrier-grade Wi-Fi* [6]. Compared to a typical macrocell whose coverage is up to several tens of kilometers, a small cell coverage ranges from dozen to few thousands meters. Typically, a Femtocell may transmit radio signals at a maximum

[4]Source: Cisco VNI Mobile, 2016
[5]Source: Cisco VNI Mobile, 2016
[6]Source: Small Cell Forum

power of 23dBm, which can reach up to 50m. A Picocell signal transmit power is 23-30 dBm, and its coverage is up to 200-300m. A Microcell has wider coverage radius: up to 2km; it has a transmit power of 30-46dBm. Wi-Fi access point range depends on technology, but does not exceed 250m. It transmits at about 25dBm.

The smallness character of small cells provide this technology with attractive features. Firstly, they enable providing better coverage. Micro cells are basically designed to extend coverage for indoor/outdoor users where macro coverage is insufficient . Furthermore, Femto cells in Macro-joint deployment enable to improve coverage, especially in less dense deployment scenarios. Actually, the Japanese mobile operator Softbank had a success story in deploying Femto cells with specific outdoor engineering design in order to cover isolated villages and localities. Small cells have lower power requirements: as small cells are based on small sized base stations, they require less energy resources either for signal transmission or equipment consumption. Dense deployments of small cells are promoting significant energy consumption reduction. When used with sleep mode, they have an observable impact on Radio Access Network (RAN) energy efficiency. Small cells have lower costs. Indeed, lower energy requirements are automatically interpreted as costs savings. Moreover, small cells equipment costs much less, which enables to achieve profitable cost savings. Finally, small cells are easy to deploy since they come in medium to small boxes, easy to replace and connect, and do not require large spaces.

Why should we care and what can we do?

Inspired by the potential advantages of small cells networks, some MNOs are seriously envisioning small cells as an alternative solution for covering areas where the operator does not own or control transport infrastructure. In fact, small cells might be deployed as the the only access nodes, in spaces where no access infrastructure is settled to ensure MNO broadband connectivity. However, the cost of deploying transport infrastructure is high in comparison with the population revenue. It is no more economically beneficial to serve such populations. Backhaul business plan should not be a barrier to small cell deployment in green-field areas.

In this respect, wireless technologies (like Microwave, Satellite or Wi-Fi) are strategic solutions to reduce transport networks' costs and hence facilitate small cells deployments. There are some limitations affecting wireless backhaul infrastructure compared to wired ones (such as Fiber or cable); one of the most crucial is low data rates. The small cells backhaul must be able to transport end users traffic flows without sacrificing network performance.

In this thesis, we address some of small cells wireless bakchaul challenges, intended to cover green-field areas where no operator wired infrastructure is available. For this purpose, we focus on respecting service areas demands in terms of capacity, while keeping in mind the deployments and economic constraints.

In the first instance, we deal with small cells backhauling with minimal required links capacities and aggregators, in such a way that incurred cost is the lowest possible. Since wireless technologies provide different capabilities like links capacity and range, their cost vary as well. We want to provide the most suitable backhaul configuration that respects most, if not all those parameters. Then, we deal with the influence of end users traffic on carried traffic by a single small cell interfaces. End users devices dictate the required bandwitdh in the backhaul segment.

In a second phase, we concentrate on enhancing WLAN cpacity performance. This is because Wi-Fi has a double role in future small cells: in the one hand, Wi-Fi links are one of the most cost-efficient solutions for backhauling; on the other hand, small cells technologies cover also small-size low-range wireless access nodes based on IEEE 802.11 standards. Wi-Fi systems should support symmetrical performance on both downlink and uplink directions. Nonetheless, the system capacity in uplink transmissions is not yet developed enough to reach downlink levels.

Contributions

Deploying small cells in uncovered areas is strongly associated to delivering minimum QoS services at lower cost and deployments complexity. Even though small cells solutions are low cost/easy to deploy radio access nodes, their backhaul should be also cost-effective while providing good quality connectivity. The choice of the most suitable wireless backhaul solutions is driven by end user requirements by respect to throughput over space and time. The backhaul may include different solutions for the same RAN: Wi-Fi is a promising one, especially for WLAN small cells. The latter may reach high capacity when some advanced techniques are implemented: UL MU-MIMO is a key enabler for WLAN system and user uplink capacities.

This thesis consists of two parts. In the first part, we analyze cellular small cells backhaul proprieties, then we propose two approaches to improve backhaul dimensioning regarding required end users traffic demand.

The first approach aims at making backhaul solutions decision by respect to some constraints:

- **Cost-optimal planning in a green-field small cells networks**: we consider an access network fully covered by small cells. This RAN has access to at least one operator service aggregation node. We propose a cost-efficient model that minimizes incurred backhauling costs while respecting three main constraints: links capacities, links ranges and uniqueness of the aggregation node. Computation results corroborate cost-efficiency of wireless solutions over wired connections; and provide guidelines for wireless hybrid backhaul solutions.

In a second stage, we focus on evaluating the impact of end users devices activity on carried traffic by logical interfaces of a single small cell:

- **Small Cells Network Planning based on Traffic Analysis**: the invested wireless backhaul solutions depend on service area needs in terms of traffic; this one is directly related to the amount of data exchanged between end users devices and service network. We propose a traffic analysis based on Markov model. The analysis assesses the influence of UEs activity on a small cell logical connections traffic flows. We provide also a classification of UE traffic depending on which logical interface it travels (S1 or X2), and on its type (control or user plane).

The second part of this dissertation is dedicated to the design, analytic evaluation and implementation of a UL MU-MIMO scheduling protocol for WLAN.

- **Enhancing Uplink Multi-Users MIMO systems capacity**: UL MU-MIMO techniques are not yet normalized by any WLAN standardization body although they are promoting alternative for capacity improvement. We design a MAC protocol that enables to schedule a UL MU-MIMO transmission while being backward compatible with current IEEE 802.11 standards; i.e. to exchange minimal control frames between multiple transmitters and the receiver. We evaluate its system performance by a semi-Markov model. Finally, we propose an enhanced version that even reduces overheads, and provide then proof-of-concept simulations for the efficiency of two versions.

Thesis Organization

This dissertation is divided into four chapters.

In Chapter 1, we introduce the general technological context of small cells networks; particularly, we briefly survey architectural aspects, backhaul requirements and wireless solutions and UL MU-MIMO transmissions for WLAN small cells.

In Chapter 2, we propose the cost-optimal data aggregation model for small cells backhaul in green-field deployments. We compare wired and wireless backhaul solutions for many network sizes, network loads and levels of operator presence.

In Chapter 3, we analyze the impact of end users activity on generated throughput on a single small cell logical interfaces (S1 and X2). In this analysis, we consider different UE throughput components that travel through each logical interface.

In Chapter 4, we propose a new MAC scheduling protocol for UL MU-MIMO transmissions in WLAN in two versions; basic and enhanced. We then evaluate its theoretical performance via modeling. At the end, we provide intensive simulations discussions on both versions of the scheduling protocol, compared to SU scheme.

The conclusion chapter summarizes the main contributions of this thesis and discusses remaining open questions.

Chapter 1

Small Cells Networks: Technological Glimpse

Contents

1.1 Introduction

Providing proper solutions for coverage deployments using only small cells requires a good understanding of the technical features of this technology; not to mention the technological limitations: they should be clearly pinpointed in order to address them for maximum benefit. The purpose of this chapter is to give a state-of-the art overview of the technological background on small cells deployments, particularly in areas where the operator has no transport infrastructure. Firstly, the logical architecture that may drive small cells deployments are sketched for two main technology families: cellular (3G/4G) and WLAN. This leads to frame the backhaul segment and to list its key requirements for reasonable operations. One of the critical requirements is low installation cost. A cost-efficient backhaul is primarily based on wireless solutions. In this optic, most mature wireless technologies are evaluated regarding the predefined backhaul requirements. Finally, Wi-Fi is foretasted to play a massive role in future small cells networks for two mains reasons: 1) Wi-Fi access nodes, i.e. Access Points, are increasingly deployed in radio cellular network (e.g.: for offloading), 2) Wi-Fi links are considered a cost-efficient solution for the capacity they provide. However, since they are intended to ensure backhauling between small cells, i.e. two-ways communications, they should grant symmetrical capacity performance in both downlink and uplink. Yet, the uplink capacity is limited in WLAN technology family. It may be boosted by embedding novel techniques like Multi-users transmissions.

The rest of this chapter is structured as follows. Sections 1.2 parses both cellular (3G/4G) and WLAN small cells networks architectures. Section 1.3 outlines the most relevant small cells backhaul requirements for green-field deployments. Section 1.4 discuses available wireless backhaul technologies by report to mentioned requirements. Section 1.5 explains UL MU-MIMO transmissions in WLAN, then identifies the main challenges facing its adoption. Lastly, Section 1.6 concludes this chapter.

1.2 Legacy Architectures

1.2.1 3GPP: 3G/4G

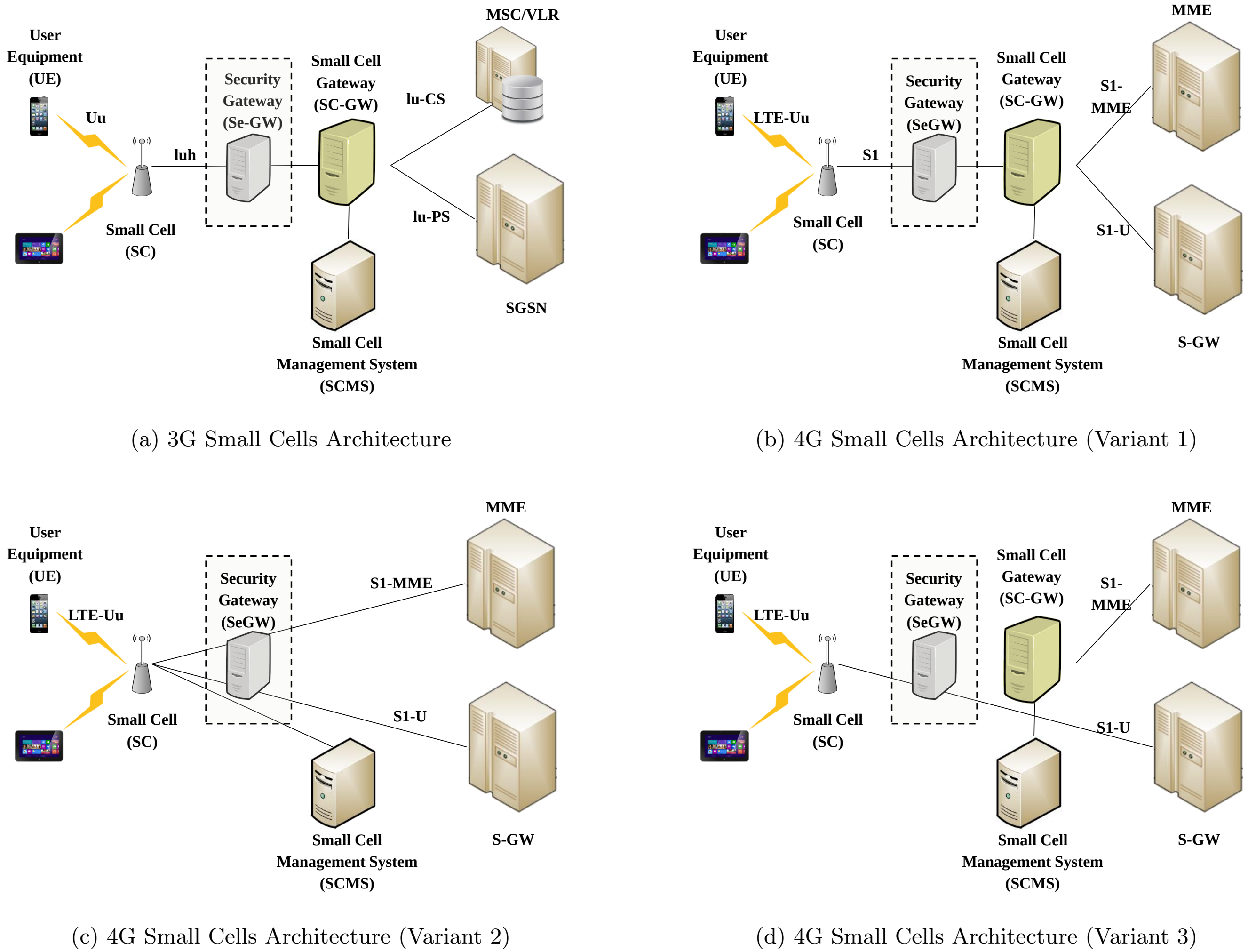
3G/4G Small cells are low-power cellular base stations that use licensed spectrum. Although Femto cells technology were first designed for residential environment, its use was extended to other usages such as enterprise, public hotspots and rural areas. Pico, Micro or Metro cells are the cellular extensions of Femto cells into cited environments. The 3GPP has standardized 3G/4G Femto cells architceture and protocols [5]. The 3GPP defined the terms: Home Node B (HNB) for UMTS femto cell and Home eNodeB (HeNB) for a LTE femto cell. As Femto cells usage has evolved, their 3GPP architecture specifications may evolve to include other cellular Small Cells architectures specifications too. Hereafter, architectures of HNBs and HeNBs are detailed and are considered to be valid for all cellular Small Cells types. The "Small Cell" term comprises HNB/HeNB and other types of smaller cells.

The logical architecture for 3G small cells is shown in Figure (1.1a). 3GPP has defined three variant for 4G small cells architectures (Figures (1.1b), (1.1c) and (1.1d)). The variants differ from each other in terms of the deployment of Small Cell Gateway (SC-GW) in the system or not, and when deployed whether it terminates the control plane only or both the control and user planes. Those variants were standardized in order to meet different operator deployment scenario requirements.

LTE is characterized by the introduction of new interface between access nodes for handover and interference managements: it is the X2 interface. As 3G/4G macro cells characteristics and functions apply to 3G/4G small cells respectively, two facts are made: 1) 3G small cells are not connected to each other, and 2) 4G small cells are connected to their neighbors small cells via X2 interface.

In this thesis, the focus is given to LTE small cells rather than 3G small cells. Table 1.1 [5]-[36]-[51]-[37] describes the differences between the three LTE SC architecture variants. Tables 1.2 and 1.3 [5]-[36]-[51]-[37] compare the advantages and limitations of each variant, by considering the messaging impact of main used protocols. The impact of transport layer protocols like Stream Control Transmission Protocol (SCTP) and User Datagram Protocol (UDP), and of the data carrying protocol GPRS Tunneling Protocol (GTP) are discussed. Table 1.4 summarizes the applicability of each variant to different operator deployment scenarios.

As introduced before, the main scope of this thesis is the deployment of small cells for coverage in green-fields. The number of deployed SCs nodes is expected to be quite huge to support end users requirements. For this reason, the variant 1 of 3GPP LTE architecture is kept as reference architecture for this work. Variant 1 is the most suitable architecture for a large deployment of small cells in distant sites from operator transport network. Figure 1.2 summarizes the considered small cells architecture.



(a) 3G Small Cells Architecture

(b) 4G Small Cells Architecture (Variant 1)

(c) 4G Small Cells Architecture (Variant 2)

(d) 4G Small Cells Architecture (Variant 3)

Figure 1.1: 3GPP Small Cells Architecture

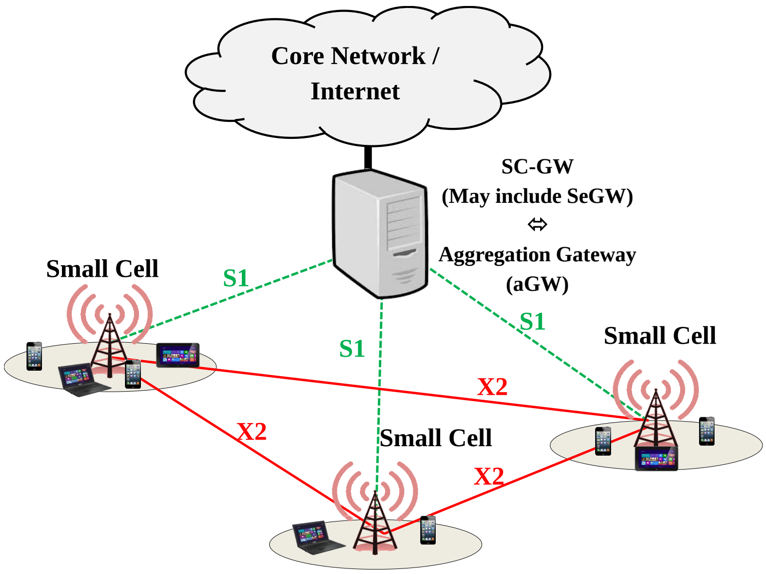


Figure 1.2: Aggregated Cellular Small Cells Architecture

1.2.2 Operator WLAN

Wireless LAN technologies are an excellent broadband complement for the operators' existing 3G/4G services.

Figure 1.3 shows a simplified version of an operator WLAN architecture in non-roaming model. Only connections between the WLAN access and Operator core networks are described herein [4]-[10]-[61].

Network elements:

- **WLAN UE**: a WLAN UE is the User Equipment that may be capable of WLAN access only, or it may be capable of both WLAN and 3GPP radio access.

- **Access Point (AP)**: it represents the access node on the network and is assimilated to be the WLAN small cell. It is the central transmitter and receiver of wireless radio signals and ensures broadband access to WLAN UEs. An AP can operate independently if the wireless network is established over a small distance, or managed by a controller in large area wireless networks. Some APs support mesh networking by allowing a radio for clients and other(s) for point to point connection to other(s) AP(s).

Table 1.1: Specifications of 3GPP LTE Small Cells Architectures Variants

	Variant 1	**Variant 2**	**Variant 3**
Description	SC-GW serves as a concentrator for both C-Plane and U-Plane.	C-Plane and U-Plane of SC are terminated in MME and S-GW respectively.	SC-GW is deployed and serves as a concentrator for the C-Plane. The user plane of SC is terminated in S-GW.
SC	The Access Point: it supports the same functions as a Macro Cell and same procedures to/from EPC as the Macro Cell too.		
SC-GW	SC-GW connects between MME/S-GW and SC	No SC-GW: SC is directly connected to MME and S-GW	SC-GW connects between MME and SC and the latter is directly connected to S-GW
SeGW	It is a mandatory logical function between SC and core network elements (SC-GW if present and S-GW/MME). The SeGW may be implemented either as a separate physical entity or co-integrated with an existing entity. The SeGW secures the communication from/to the SC.		

- **Access Controller**: in large scale areas where many access points are deployed, it is necessary to use an access controller to manage them. Controllers perform more critical functions for WLAN access maintenance, such as APs configuration, interference managements and load balancing. The AC may enable local Intranet/Internet access for the WLAN access network.

- **WLAN Access Gateway (WAG)**: it is a gateway that ensures Packet Switched (PS) data carrying between the the WLAN access and operator networks. It is the interworking point between the WLAN access and cellular services networks. It collects information related to charging and per tunnel accounting and enforces routing of packets through the PDG.

- **3GPP Authentication, Authorization, and Accounting (AAA) Server**: It is located in the 3GPP network. An attached WLAN subscriber is associated

Table 1.2: Advantages of 3GPP LTE Small Cells Architectures Variants

Variant 1	1) More secure architecture (MME and S-GW IP addresses are hidden from SC.) 2) Less SCTP associations to the MME: less SCTP messages overload in the MME and hence less CPU processing. 3) Enhanced S-GW scalability for UDP/IP and GTP protocols: S-GW manages less UDP/IP paths and GTP Echo messages which enables to deploy more SCs. 4) This variant allows to implement many mechanisms in the SC-GW such as: Paging optimization, Traffic offload, Denial of Service (DoS) and Handover optimization. Those mechanisms permit to unload and protect core network elements.
Variant 2	1) Less failure points in the system: a SC failure will not affect other SCs functioning. 2) Lower latency and reduced system level processing is achieved: direct connection to the core network elements. 3) Less upgrade/compatibility issues in supporting new releases features since SC-GW is not deployed. 4) SIPTO gateways can be deployed in distributed manner.
Variant 3	1) Less SCTP associations to the MME: less SCTP messages overload in the MME and hence less CPU processing. 2) This variant allows to implement many mechanisms in the SC-GW such as: Paging optimization and Handover optimization. Those mechanisms permit to unload and protect core network elements. 3) Lower latency and reduced system level processing is achieved in U-Plane: direct connection to the S-GW.

only to one 3GPP AAA server. It performs all Authentication, Authorization, and Accounting (AAA) procedures as for a cellular UE. A 3GPP AAA proxy interconnects between 3GPP AAA Server and WAG in roaming models; it is a proxying and filtering function located in the 3GPP network.

- **Packet Data Gateway**: it is the cellular gateway (3G/4G) that allows to access 3GPP PS based services. It acts as an anchor for user plane mobility and performs most of its functions as for a cellular access network (e.g. user

Table 1.3: Limitations of 3GPP LTE Small Cells Architectures Variants

Variant 1	1) SC-GW performs GTP-U tunnels switching in downlink/uplink: this infers on a U-Plane processing load proportional to traffic. 2) Less flexibility in redundacy and load sharing since a SC connects to a single SC-GW at one time.
Variant 2	1) Distributed SSCBC/GTP-U connections and UDP/IP contexts leads to overload situation in MME and S-GW, which increases CPU processing load in the core network especially in huge SCs deployments. 2) In case dedicated MME/S-GW are required to solve overload problem, additional GW relocation load should be processed.
Variant 3	1) No GTP-U connection concentration leads to overload situation in the S-GW due to UDP/IP contexts and GTP-U Echo messages, especially in massive SCs deployments. 2) Less flexibility in redundancy and load sharing in C-Plane since a SC connects to a single SC-GW at one time.

traffic filtering for QoS differentiation, WLAN UE IP address allocation, etc).

- **Wu**: it is located between the WLAN UE and the PDG and is transported by Ww, Wn and Wp reference points. It is not a direct interface between WLAN UE and PDG but represents an initiated tunnel for data between the two elements.
- **Wn**: it is the reference point between the WLAN Access Network and the WAG. It forces the traffic crossing via the WAG on a WLAN UE initiated tunnel.
- **Wp**: it is the reference point between the WAG and PDG and would be defined by the operator/technology.
- **Wa**: it is the reference point between the WLAN Access Network and the 3GPP AAA Server. It serves to transport authentication, authorization and charging information, possibly via intermediate networks, in a secure manner.
- **Wm**: it is the reference point between the 3GPP AAA Server and PDG. It serves to carry user AAA messages between the two elements.
- **Wg**: it is the reference point between the 3GPP AAA Server and the WAG.

Table 1.4: Applicability of 3GPP LTE Small Cells Architectures Variants

Variant 1	1) A good choice for the operator to a fast and cost-efficient migration from a 3G to 4G SC solution for two main reasons: i) this variant is comparable to 3G SC architecture terminating both control plane and user plane in the Gateway, and ii) existing GW infrastructure components (Platform/ Hardware Reuse, User plane handling / GTP functionality reuse) can be easily reused and upgraded. 2) It is a beneficial solution for new and massive LTE SCs deployments: as many mechanisms are handled by the SC-GW, the core network is protected from huge processing load of numerous SCs nodes. It also allows to minimize the impact of EPC as much as possible when number of deployed SCs is increasing.
Variant 2	1) For 4G upgrade deployments, this variant can re-use SeGWs and transport infrastructure from 3G architecture. 2) This variant is beneficial in deployments scenarios where the number of SCs is limited to a threshold that reduces cost effect and does not create scalability issues on the core network. It relates essentially to residential deployments, but still depend on MME capacity to handle SCBC connections.
Variant 3	1) For 4G upgrade deployments, this variant can re-use SeGWs and transport infrastructure from 3G architecture. 2) As the number of deployed SCs increases, S-GW scalability requirements increase too. Fair evaluation of UDP and GTP contexts impact should be considered on case by case basis.

It is an AAA interface. It provides the WAG with necessary information to perform policy enforcement functions for authorized users.

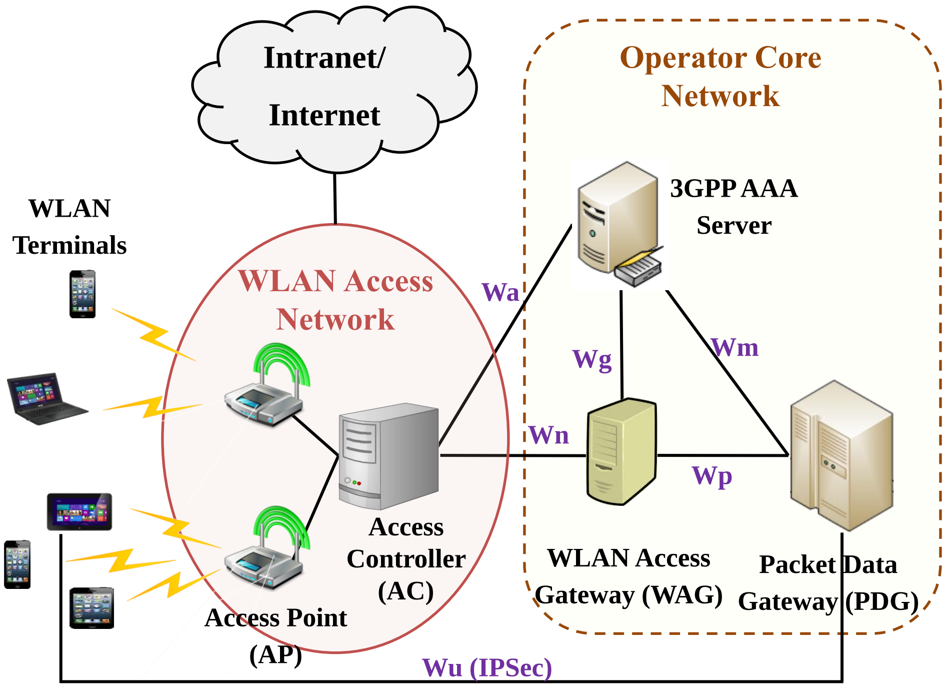


Figure 1.3: A simplified Operator WLAN architecture

1.3 Small Cells Wireless Backhaul Requirements

The backhaul is the network segment that provides connectivity between access nodes (i.e. small cells) and core network at a certain level of QoS, and between access nodes themselves. The backhaul is made up of a set of transport network aggregation points that ensures the connectivity function it is designed for. Namely, the backhaul possesses at least one Point of Presence (PoP) or Point of Concentration (PoC). The PoP/PoC acts as a central aggregation point for different small cells traffic towards the core network. By referring to our SCs reference architecture (figure 1.2), the aGW (i.e. SC-GW) may play this role. Actually, the aGW may either aggregate many SCs and being itself aggregated by a PoC, or may enable both aggregation and connectivity for the SCs. In this thesis, the focus is given to the part between SCs and the PoC node; connectivity between the PoC and operator core network is assumed to be available whatever the access solution is.

In the following subsections, main challenges that face small cells wireless bakchaul in green-field deployments are discussed [58]-[57]-[38]-[14]-[26].

1.3.1 Connectivity

Furnishing a good quality connectivity between SCs and core network is strongly associated with PoC coverage: it denotes the area where a set of SCs can connect to the PoC at minimum quality. Indeed when wireless technologies are intended to be used in the bakchaul, Line-of-Sight (LOS) or Non Line-of-Sight (NLOS) links and Point-to-Point (PtP) or Point-to-Multipoint (PtMP) communications should be considered.

LOS wireless links requires clear links -without/with minimum physical obstructions- between SCs and PoC. In this case, wireless links may suffer from atmospheric attenuation [53]-[54] and long distances. NLOS wireless links can be considered: used alone or coupled with LOS ones. It all depends on the physical characteristics of the service area to cover with small cells and operator network availability.

In green-field deployments where the PoC is supposed to serve large areas with numerous SCs, it is more convenient to favor PtMP communications since it does not require antenna alignment. Yet PtMP communications endures low capacity due to huge SCs traffic multiplexing and limited spectrum availability at lower frequencies.

Depending on cost requirements and operator availability, small cells covering an area can be connected to any connectivity node that offers most convenient backhaul. A small cell can either connect directly to the PoC (and/or aGW) or to another small cell. The operator may use a mixture of tree and mesh topologies to provide an effective connectivity.

1.3.2 Throughput/Capacity

The backhaul capacity must at least fulfill the entire associated small cells capacities. Moreover, it should follow future traffic growth and support its daily variations. Considering the worst case scenario when dimensioning the backhaul capacity is not an efficient solution since it would lead to an over-provisioning. In fact, a high provisioning level for backhaul capacity means that more PoCs and links are needed and higher capacity links are required. The backhaul solutions are hence more expensive and can be more complex to deploy.

A backhaul provisioning method was adopted by the NGMN Alliance [11] that takes into consideration two load cases of the network: busy hours and quiet hours. Actually, wireless backhaul is very sensitive to available bandwidth, shared radio resources and signal noises. This implies that an end user throughput depends on the quality of its radio link. During busy hours, many end users devices share the small cell resources: it is unlikely that all users have a link good enough to transmit/receive at maximum spectral efficiency. Consequently, the required capacity by the small cell corresponds, in this case, to the mean capacity of all its users. During quiet hours, it is generally one end user device that can use the entire small cell resources. When its radio link is of a good quality, this user can reach the peak throughput. In this case, the small cell capacity's need is measured by report to this value. However, end users throughput fluctuates depending on various parameters. By assuming that busy time means do occur simultaneously and that quiet time peaks do not, the backhaul capacity provisioning for N small cells is obtained as: *Max (peak,* $N \times$ *busy time mean).* Nowdays, a 3G/4G link may require up to 60 Mbps in uplink an 200 Mbps in downlink [60] depending on 3GPP's feasibility study on LTE Advanced [9]. The simulations pointed out how *cell spectral efficiency in the microcell environment is on average 25% higher than in the macrocell environment.* Although the analysis focused on dense deployments, small cells spectral efficiency is assumed to be 1 to 1.25x to macro cell spectral efficiency.

1.3.3 Delay

Mobile broadband is foretasted to include a great amount of delay-sensitive services, especially the ones that require real-time interaction such video conferencing, gaming, etc. Delay and jitter degradation impacts the Quality of Experience (QoE) of these services users. Not only data traffic may be impacted by end-to-end delay degradation, but also signaling messages (e.g. X2 signaling for interference cancellation). As the end-to-end delay is measured between the user terminal and the service server, the backhaul, connecting radio to core, contributes in this delay.

3GPP introduced to the LTE networks the QoS Class Identifier (QCI) mechanism that allows to allocate appropriate QoS. 3GPP recommends in [69] packet delay budgets for many service types depending on their QCIs. The recommended delay budget from the UE to the EPC ranges from 50 ms (i.e. gaming) to 300 ms (i.e. default best effort). Those recommendations are made for worst case scenario, hence they represent the minimum acceptable QoE; operators may exceed those figures at reasonable level.

When establishing the delay budget, it is necessary to identify the network components that will be involved in this delay. Typically, there are components that are always deployed, which introduce their own delay, such as radio interface or transport segment between the PoC and CN; other components are not always deployed and their delay impact is considered per use case solution: SC-GW is an example. Moreover, the backhaul delay remains negligible compared to the largest latency generated by any other component. The SCF [34] suggests these small cell backhaul delay assessments:

- $<$ 1ms: Negligible
- 1-10ms: Low
- 10-60ms: Acceptable
- $>$ 60ms: Acceptable/Depends on the service

1.3.4 Security

The SCs backhaul security requirements is based on the assessment of SCs network: trusted or untrusted. The trusted/untrusted notions are introduced by 3GPP [7] depending on different *trust* criteria; for example: operator security level, physical site locations control, network management levels, etc. The 3GPP specifies to implement an extra mandatory layer of security for untrusted networks. A customized investigation should be conducted by the operator in order to evaluate eventual risks.

As for the macro cells, it is assumed that 3G/4G small cells backhaul belongs to trusted networks as stated by 3GPP architecture models [6]. The IPSec framework is adopted for such networks as recommended by 3GPP. The operator still has the choice to deploy or not IPSec communications; however it is preferable to implement it since it would prevent any potential vulnerability.

The communications between a small cell and the core network should be secured by IPSec tunnels. The IPSec framework ensures data integrity, authentication and confidentiality to guarantee the end-to-end service protection [12]. As introduced in subsection 1.2.1, a small cells network deployment should include a mandatory Se-GW, either as an integrated logical function with SC-GW or one of EPC, or as a separate physical node. The operator is free to choose the implementation point/way of the Se-GW depending on its deployments requirements.

Regrading Wi-Fi small cells, two types of access are defined (according to 3GPP): trusted and untrusted 3GPP Wi-Fi access [3] . As Wi-Fi was considered open and unsecured by default, 3GPP introduced the untrusted access in the Wi-Fi specification in 3GPP Release 6 (2005). It refers to Wi-Fi APs non-controlled by the operator, especially the ones with alleviated security mechanisms. The untrusted access model requires an IPSec client in the WLAN terminal. Communications between the WLAN device and the PDG (Figure 1.3) are secured via IPSec tunnel; whereas the user session is transported through a secure tunnel (GTP or PMIP) to the P-GW.

Trusted access was introduced lately in LTE standard in 3GPP Release 8 (2008). It is assumed to be built by an operator. Wi-Fi radio access network is encrypted and network access is secured via an authentication method (802.1x [1]-based and Extensible Authentication Protocol (EAP) methods). The communications between WAG (Figure 1.3) and core network are secured via GTP, Mobile IP (MIP) or Proxy Mobile IPv6 (PMIP)).

1.3.5 Synchronization

As 3G/4G systems, small cells base stations require frequency synchronization to satisfy spectrum license conditions and for stable operation of the system (e.g. handovers). The SC radio frequency accuracy is required to range from 50 parts per billion (ppb) (largest Micro cells) to 250 ppb (Femto cells).

Time Division Duplex (TDD) systems requires additionally phase synchronization to ensure downlink and uplink timeslots of adjacent cells not to coincide. Small cells requires a phase difference less than 3μs between adjacant cells, which corresponds to a phase synchronization of $\pm 1.5\mu$s.

Advanced features such as Coordinated Multipoint (CoMP), enhanced Inter-cell interference coordination (eICIC) and carrier aggregation requires additional time synchronization. Although the accuracy requirements were not defined for each technique, it is intended to be around $\pm 1\mu$s.

To sum up, synchronization accuracy requirements will depend on the synchronization demand of the planned small cell radio to manage intercell interference [25].

[1] It is an IEEE standard that provides an authentication mechanism to WLAN terminals.

By taking into account small cells synchronization features, their backhaul synchronization needs may be identified. Many techniques are available to ensure synchronization for small cells. In fact, synchronization can be provided by: 1) frequency/packet-based timing reference over the backhaul network (Synchronous Ethernet (SyncE), Network Time Protocol (NTP), etc), 2) by radio (e.g. Global Navigation Satellite Systems (GNSS)), and 3) local built solution like an atomic oscillator. Moreover, not all those techniques enable the three types of synchronization, as an example, SyncE can ensure only frequency synchronization. Not to mention that other techniques may be exposed to signal losses especially in indoor deployments; like GNSS.

The impact of delay/jitter of packet network should be considered in the quality of provided synchronization to small cells: offsets correction may be applied. In all cases, backhaul should at least meet 3GPP minimum requirements for small cells regarding frequency accuracy (at least ± 50 ppb) and phase accuracy for TDD system ($\pm 1.5\mu$s).

1.3.6 Low Installation Cost

In the use case deployment we target in this thesis, small cells are intended to replace macro cells in ensuring coverage since they have economic advantages. The backhaul cost is one of the key parameters that drive this use case deployment as it is an integral part of planned small cells networks. First, the number of small cells that would be deployed as a substitution to macro cells will be large in order to transport the same amount of traffic; as a consequence, more backhaul links are needed, each by which is characterized by its own cost. Second, forecasted technologies to backhaul the small cells should be adapted to previously discussed backhaul requirements, the technologies that meet the majority of them would cost more. Hence, it is vital to analyze the Total Cost of Ownership (TCO) of small cells backhaul.

The SCs backhaul TCO is essentially made up of OPEX and CAPEX. They refer to all the costs generated by deployment and operational processes during the backhaul life cycle. Those costs can further be divided to fix (initial) and variant (ongoing over years) costs.

OPEX and CAPEX depend primarily on two parameters: 1) features of exploited technologies for backhauling and 2) backhaul topology. Linking technologies may differ from each other in network planning and installation costs for example; some

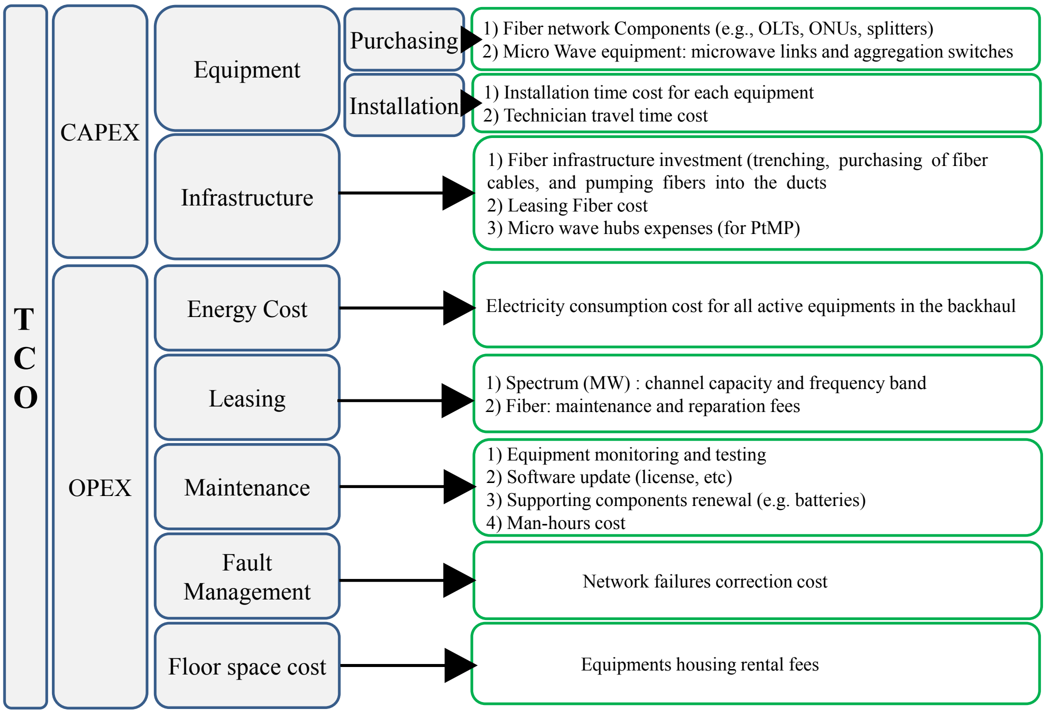


Figure 1.4: Mobile Backhaul TCO components [49]

have specific costs spectrum license fees for microwave. The wireless backhaul is the most sensitive to planned topology: PtP or PtMP. The analysis proposed in [62] points out that a SCs backhaul with PtMP (NLOS) topology can provide up to 59% TCO savings compared to PtP (LOS) topology.

A valuable mobile backhaul TCO modeling was suggested in [49]. This model proposes a detailed classification of a mobile backhaul TCO components by taking into consideration different types of linking technologies and used typologies. Figure 1.4 summarizes the TCO of a mobile backhaul. The benefit of such modeling is the ability to assess the implication of each links in incurred cost, even in heterogeneous bakchaul networks. This classification is easily applicable to small cells networks.

The financial analysis of Senza Fili Consulting [55] based on backhaul TCO classification compares CAPEX and OPEX between fiber, microwave, E-band PtP and microwave PtMP backhaul for 3G/LTE macro cells and LTE small cell networks over a period of five years. The analysis demonstrates how wired backhaul (i.e. fiber) incurs massive cost compared to wireless one. Actually, figure 1.5 depicts a comparison of cumulative CAPEX and OPEX per Mbps within 3G/LTE networks over 5 years.

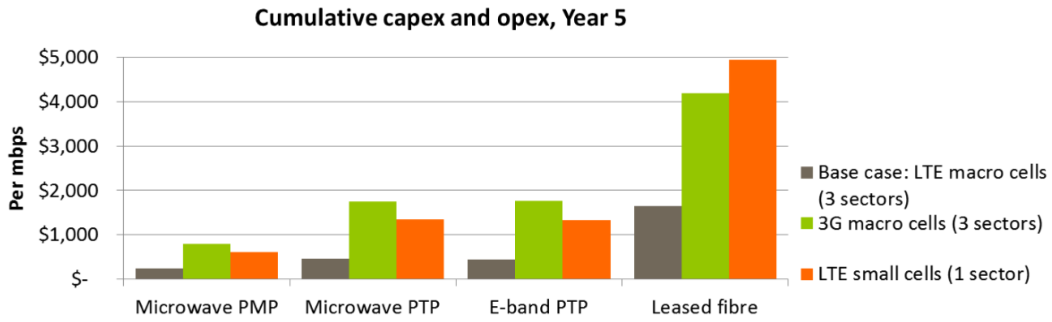


Figure 1.5: Comparison across scenarios of cumulative CAPEX and OPEX per Mbps after 5 years. (Source: Senza Fili Consulting) [55]

Senza Fili Consulting analysis enables to make a recommendation regarding small cells backhaul cost requirement: the latter should not incur CAPEX and OPEX that exceed macro cells backhaul, designed for the same coverage purpose. Wireless links are hence favored over wired ones to meet this requirement.

1.4 Wireless backhaul links

Wireless Backhaul solutions may be classified into categories according to some parameters: frequency bands ranges, propagation type (LOS/NLOS), connectivity topology (PtP/PtMP) and spectrum licensing [34]. In this section, an overview of existing wireless backhaul solutions regarding precedent parameters is provided [63]-[39]-[31]-[26]-[48]-[58]-[57].

1.4.1 Millimeter wave

The millimeter wave (mmWave) links operates in the spectrum of 57–66 GHz (V-band) and 70–80 GHz (E-band) bands. These high frequencies enable high capacities, but at short ranges. Transmissions on these bands use highly directive narrow beamwidth antennas in the large spectrum, which allows to substantially minimize interference. Propagation characteristics and channels abundance permits to provide Gbps (and more) of throughput using simple single-channel configurations. This design simplicity has an advantageous cost-per-bit in high capacity backhaul. Moreover, their low licensing costs make them more financially attractive solution.

However, mmWave technologies are very sensitive to atmospheric attenuation (caused mainly by oxygen or water molecules). Heavy or excessive rainfall environments are potentially affected. Moreover, the very short wavelength of this technology results in high attenuation due to tough diffraction and penetration through obstacles, only LOS connections are feasible.

1.4.2 Microwave

Microwave (MW) is a high capacity communication technology that operates in the spectrum between 6 GHz and 60 GHz bands. These frequency carries imply short wavelength, the signal experiences high losses due to diffraction and penetration through obstacles; LOS connections prevail MW propagation, nevertheless near LOS (nLOS) connections are still practicable at lower frequencies. Though short wavelength enables the use of compact directional antennas with high gain and narrow beamwidth (with antenna alignment for minimum performance). The obtained high gains in LOS propagation make MW backhaul very convenient to long range fixed links. Careful planning should be performed in frequencies above 10 GHz: the signal endures significant attenuation due to the absorption and scattering of electromagnetic waves by rain.

MW backhaul links can be used in PtP or PtMP. PtMP connections use the same type of air interface technology as PtP; however, PtMP uses a wider beamwidth antenna at the 'hub' end of the link in order to serve multiple small cell sites by a wide coverage sector. As the sector capacity is shared between multiple small cells, traffic multiplexing is realized: significant benefits are achieved with this multipoint topology due to enhanced link capacity utilization compared to PtP. A case study [1] of live data from a tri-sectored macro cell network has showed 58% improvement.

MW frequency bands are licensed according to two types: 1) per-link licensing for PtP connections: the license includes a spectrum allocation between the two end points of the link, and 2) per-area licensing for PtMP: the license includes a block of channels over a specified geographical region. The per-area licensing is more suitable for small cells deployments in green-fields, where wide areas are targeted to be served.

1.4.3 Wi-Fi

Wi-Fi belongs to wireless technologies that operates in sub-6 GHz spectrum in unlicensed bands. The sub-6 GHz frequencies ensure ubiquitous coverage and support NLOS propagation, which enables PtMP connectivity. Omnidirectional antenna are used to deliver the radio signal without any requirement on antenna alignment. The unlicensed deployments of Wi-Fi are an attractive backhaul solution for three main reasons: 1) the available contiguous spectrum, 2) flexible deployments and 3) cost-optimal (no license acquisition).

However, the signal may suffer from severe interference. Actually, the unlicensed nature of Wi-Fi spectrum means it is an uncoordinated spectrum, which causes adjacent channel and co-channel interference. Frequency reuse and coordination techniques should be adopted to mitigate interference effect. Another challenge that faces Wi-Fi links is its contention-based protocols. Although those protocols allow interoperability and co-existence among competing radios using the same radio channel, they may favor interference between competitors, especially between different operators, unless the latter define radio access policies to self-correct it. Wi-Fi may also suffer from traffic congestion.

Wi-Fi performance depends on both underlying technologies (e.g.: FDD and TDD) and vendors implementation designs. The operator should be aware of accordance of vendor and product selections. Wi-Fi capacity is frequently evaluated as aggregate bandwidth: it ranges from tens of Mbps to many Gbps (almost 7 Gbps with 802.11ac). This variety in capacity range is due to the use (or not) of enhanced techniques like packet aggregation, high coding and modulation schemes and multi-users transmissions. Many experimental studies show how IEEE 802.11n/ac technology can meet small cells backhaul requirements in terms of capacity, latency and jitter [34]-[44].

1.4.4 Satellite

Satellite technologies operates in different bands: e.g. C-band (4–6 GHz) and Ku-band (10–12 GHz). Hence the signal attenuation will depend on the used frequency. C-band frequencies are practically unaffected by weather and rain fade; whereas Ka-band (20–30 GHz) is highly impacted.

Satellite backhaul has the advantages of practically universal availability (where satellite is visible) and rapid deployment times. However, it incurs ongoing OPEX related to rented bandwidth from satellite network operators (SNO). SNOs provide with the satellite service (including installation, management and repair). MNOs may occasionally manage a satellite network only if it is proved to be more advantageous to proceed this way. Otherwise, MNOs can rent links from SNOs: the rented components in the satellite link are the remote terminal equipment and satellite bandwidth.

Satellite can offer up to 350 Mbit/s capacity. Nonetheless, the size of the dish and power amplifier increase with capacity. Not to mention the operational cost that is proportional to required capacity, this causes higher costs [35].

The use cases for which backhaul satellite would be deployed are very limited: targeted capacity hotspots.

1.4.5 TV white spaces

The TV band comprises two bands: VHF band (54–60 MHz, 76–88 MHz, 174–216 MHz) and UHF band (470–698 MHz). TV white spaces (TVWS) refer to vacant spectrum resulting on the use of digital TV (DTV) transmission. TVWS can still be used for licensed TV transmission, whilst they can provision small cells backhaul in unlicensed bands.

TVWS channels enable better propagation properties and large foot print due to their longer wavelengths. Besides the unlicensed nature of TVWS, this helps to reduce backhaul network costs [35].

Yet, TVWS small cells backhauling will be very restricted by the transmit power and location of primary TV transmitters. Namely it would be recommended for connections between small cells only. the primary challenges of TVWS are the radio design: it must meet regulations made to protect primary users, and secondary user co-existence: interference should be alleviated in this harsh environment of unlicensed spectrum.

1.4.6 Comparative Summary

The choice of small cells network backhaul solutions depends on both operator and technological requirements (discussed in precedent section). Table 1.5 compares many wireless backhaul solutions regarding the most relevant backhaul requirements.

Table 1.5: Comparative overview of small cells wireless backhaul solutions

Technology	**E-Band**	**V-band**	**MW**	**Wi-Fi**	**Satellite**	**TVWS**
Connectivity	LOS - PtP	LOS - PtP	LOS - PtP & PtMP	NLOS - PtMP	LOS - PtMP	NLOS - PtMP
Capacity	+10Gbps	+1Gbps	+1Gbps	up to ∼7Gbps (802.11ac)	up to 50Mbit/s downlink, 15Mbit/s uplink then pay per Mbit/s	18Mbps/Channel (up to 4 channels), 80 Mbps with MIMO
Range	∼3km (hop length)	∼1km (hop length)	2-4km (at 30-42 GHz)	Up to 250m	Almost ubiquitous	∼1-5km for maximum throughput >10km: at 10 Mbps and 2 channels
Delay	65-350μs RTT single hop	sub 200μs RTT single hop	<1ms RTT single hop	2-20ms (TDD), Lower latency in FDD	300ms one-way	10ms
Cost	Advantageous cost-per-bit for high capacity links + Low TCO		Low TCO (Mature technology)	Low TCO (Mature technology)	Quite high rent costs	Low cost
Advantages	High capacity at low cost (No licensing) Scalable high capacity		High capacity Flexible propagation (LOS/NLOS) Cost saving (Area licensing with PtMP)	High capacity at low cost (No licensing) Co-existence with other links Flexible deployment	Ubiquitous coverage Efficient bandwidth share	Excellent connectivity and range
Limitations	Relatively low ranges for coverage purpose Installation complexity (antennas alignment)		Less stable PtMP links Only LOS	Narrow ranges	OPEX proportional to capacity	Harsh co-existence environment Transmit power and TV transmitters location constraints
Recommendations	Multiple hops backhauling Direct links to PoC		PtMP is preferred generally, PtP for long range Use of higher frequency bands	WLAN SCs backhaul Isolated coverage Multi-RAN use cases	Targeted area with no LOS	Last mile backhaul: between SCs

1.5 UL MU-MIMO transmissions for enhanced Wi-Fi capacity

One of the key techniques that enable high capacity WLAN systems is multi-users MIMO (MU-MIMO) transmissions. Downlink (DL) MU-MIMO is already included (as an option) in the most recent high speed IEEE 802.11ac. The uplink (UL) MU-MIMO would boost WLAN capacities, especially in high demanding areas [23]. Unfortunately, this technique is not yet considered by any of IEEE standards but intended to be an option of next IEEE 802.11ax. This section describes the technical context of UL MU-MIMO and its main challenges.

1.5.1 MU-MIMO transmissions

Conventionally (prior to 802.11n), access points have been transmitting radio waves in all directions, i.e. with omnidirectional antennas. Although omnidirectional antennas have the advantages to be cheap and to spread the signal in the coverage circle of the AP, its main drawback is that the wireless channel is busy in all directions. For this reason, an alternative method was introduced. It consists on condensing energy toward a receiver (or many receivers), it is beamforming. Beamforming technique enables the transmitter to use its antennas patterns to dynamically adjust the resulting pattern for each frame transmission. In order to make a full benefit of beamforming by making the available transmit power get to the beamformee, the channel must be measured. In 802.11ac, channel measurement is explicitly performed via frames exchange between the transmitter and the receiver. The beamformer initiates the frame exchange to the beamformee. After this frame exchange, the beamformer derives the steering matrix. This matrix contains a mathematical description of how the beamformer has to configure its antennas set so that the energy beam reaches accurately the beamformee. The frame exchange allows the two devices in question to calibrate the channel for future steer transmissions to the beamforming initiator. For example, if the AP wants to shape its transmitted frames to an end user device, it launches the frame exchange. When it is finished, both AP and STA realize their channel calibration. Then the AP transmits its data frame on a beam directed to the STA. The latter has the possibility to acknowledge the successful reception via a steered transmission in the direction of the AP. If the STA has many data frames to send to its serving AP, it can shape their transmissions by referring to its channel calibration.

Beamforming technique enabled to include multi-users MIMO in 802.11 standards. In MIMO, both transmitter and receiver exploit multiple antennas spacial diversity to improve communication performance. The capacity of channels increases by sending streams of data independently across multiple antennas. In Single User MIMO

(SU-MIMO), the AP sends in downlink (receives in uplink) the data to (from) each user terminal one after the other, with the maximum bandwidth for each device. In MU-MIMO, the AP is able to send (receive) data to (from) many users terminals at the same time, still using the maximum bandwidth of each device. Thanks to beamforming technique, MU-MIMO reduces the spatial collision domain and enhances spatial reuse. Actually, MU-MIMO beamforming permits the AP to send (receive), as many spatial streams as the number of its antennas, to (from) many end users devices at the same time.

In downlink MU-MIMO beamforming, the AP initiates the channel sounding procedure and each potential beamformmee, i.e. STA, has to feedback its channel estimation. The AP must get feedback matrices from all beamformees. So after the first station feedback, it sends poll frame to other stations to solicit beamforming report, then receives a feedback matrix from a second beamformee and sends again a poll frame; the AP continues in this way until all feedback are collected. Once is is done and that AP has built its steering matrix, it can send simultaneous frames to users in multiple streams. Each frame may be sent in its own modulation speed and coding. 802.11n supports up to four spatial streams in SU-MIMO; while 802.11ac allows a maximum number of eight simultaneous spatial streams toward up to four users, with up to four spatial streams per user. This implies that the 802.11ac restricts the maximum number of shaped beams to four, and the maximum number of spatial streams in one beam to four too.

As Uplink MU-MIMO is not supported in 802.11ac and that uplink SU beamforming is enabled only if it is initiated by the AP, there is no standardization of UL MU-MIMO in WLAN, neither of its beamforming procedure. Actually, a station may shape its transmissions to the AP, but only after the AP has launched a channel calibration procedure; moreover it is only in single user mode. However, there are many works in the literature that dealt with UL MU-MIMO beamforming in cellular networks ([59], [43], [28], [29], [30], [66], etc). It is feasible to introduce uplink beamforming at the request of end users devices in next 802.11 generations by following downlink beamforming as defined in recent 802.11ac (and stated above); however, it may be tricky to allow many devices to initiates channel calibration in the case of uplink MU-MIMO. Client device must have a minimum knowledge of channel condition to avoid collisions and hence should "collaborate" with other devices. Feedback exchanges between users would be very onerous in terms of airtime consumption. Then it is necessary that a "common" hub concentrates then share this information.

The AP is the entity that may perform such procedure. As a consequence, the AP must process each user feedback frame and inform beamformers about their uplink steering matrices.

1.5.2 Challenges of UL-MU in WLAN

One of the substantial procedures of MU-MIMO transmissions is scheduling scheme. The scheduling scheme refers to selection procedure of a set of STAs (or frames) for a simultaneous transmission, based on specific grouping rules. The scheduling scheme is performed on both downlink and uplink communications. In the downlink, the AP wants to transmit simultaneous frames to different users, depending on the scheduling methods it is using; such as round-robin, max-rate scheduler, MAC queue status scheduler, channel state scheduler, etc. Indeed, the downlink scheduling is easy to characterize since it is the AP that plays the central role of managing the multi-user transmission. However, uplink scheduling is not that simple. In the uplink, many clients devices want to send their data frames simultaneously to the AP; but they are decentralized from one another and don't have enough information in which available channel resource they can transmit in order to avoid collisions. A well designed scheduling scheme is required for UL MU-MIMO for at least three mean reasons:

- **UL beamforming preparation**: As discussed before, beamforming requires channel calibration in both sides: beamformer and beamformee. In the case of UL MU-MIMO beamforming, each beamformer should sound the channel toward the beamformee (i.e. AP), which can be costly and risky. Designing a scheduling scheme that allows an implicit channel calibration would have tremendous advantage. While exchanging information to set up the UL MU transmission, channel information may be part of the process; it would permit to reduce airtime consumption.

- **Potential transmitters grouping**: Especially when the available antennas on the AP can't serve all requesting stations, i.e. there are less resources than the number of potential MU-transmitters. The AP can only decode as many spatial streams as antennas it has. Moreover, each transmitter should have its allocated resources it can use in the UL-MU transmission in order to avoid MU collision. In this context, it is mandatory to choose among the stations the ones that will be involved in the UL-MU transmission. There are many rules that may drive stations grouping; those rules may follow downlink scheduling ones or customized as needed.

- **UL transmission synchronization**: In the cases the AP has enough antennas to serve the requesting UL-MU transmitters and after a group of potential UL-MU transmitters is selected, uplink data frames must be sent at the same instant to the AP. This is to avoid any airtime consumption and reduce transmission delays experienced by each data frame. Actually, if data frames transmissions are synchronized, the data transmission duration is at most equal to the longest frame; however, if data frames are transmitted in different instants, data transmission duration is larger and delay performance is damaged. Even if it was proved [22] that asynchronous data transmission is efficient regarding throughput, there are very few works in the literature that consider it as an eventual scenario since it adds implementation complexity. Moreover, the delay performance degradation was not analyzed.

1.6 Conclusion

In this chapter, we have described the technological context of small cells deployments in green-fields. Specifically, we have identified the main standardized architecture by 3GPP for both cellular (3G/34) and WLAN small cells (i.e. Access Points). This allows to make decision on the most adequate architecture depending in the service areas needs. Then, we have listed the most essential backhaul requirements for the deployment we target in this thesis. We have explained how backhaul installation cost is critical in this deployment context. Since wireless solutions are more suitable for fulfilling this economic requirement, we have characterized their advantages and limitations and gave a brief comparison of their features. Finally, we have explained the multi-users transmissions in WLAN systems and pointed out the implementation challenges facing the ones in the uplink direction.

Chapter 2

Cost-Optimal Planning in a Green-Field Small Cells Network

Contents

2.1 Introduction

Usually, SCs base stations (SCBSs) placements are defined by radio planning rules; then it is crucial to choose backhaul connections that provide optimal costs for the operator and ensure broadband connectivity. This implies that many linking technologies should be considered to backhaul one single SCN. This implies also that those technologies must meet both service and economic requirements.

In this chapter, we propose a cost-optimality analysis of the SCs backhauling problem when considering hybrid technologies solutions in green-field areas. In particular, SCs nodes must be backhauled to the closest Points of Presence (PoCs) of the operator at minimum cost while ensuring required broadband service. For this purpose, we propose to model the system as an optimization problem constrained by links capacities, ranges and uniqueness of the aggregation link. Solving the problem yields to retrieve numerical results for two major cases: wired and wireless backhauls. The results are compared for different parameters: network size, network load and operator presence. Comparison of those results for many SCs network parameters permits to: 1) support cost-efficiency of wireless backhaul, and 2) propose design guidelines for heterogeneous wireless backhaul. Afterwards, three access networks topologies were chosen to depict specific service areas. The topologies backhaul solutions are compared for two major methods: the optimization problem and proposed heuristic algorithms. Finally, the computational complexity of the optimal solution is assessed.

The rest of the chapter is organized as follows. Section (2.2) describes the cost-optimal scheme for aggregation data in an access network made fully of Small Cells. The section gives also solving results comparison for two set of linking technologies: wired and wireless. In Section (2.3), typical access networks are chosen to evaluate the optimization program linking solutions; the latter are compared with heuristic methods solutions. Section (2.4) discusses some practical implementation aspects of the proposed optimization problem. Section (2.5) concludes the chapter.

2.2 Cost Optimal backhaul for data aggregation

We consider an area served by $\mathcal{N}$ Small Cells. The initial placement of these cells has been performed via radio planning procedures. Only $\mathcal{R}$ SCs are directly connected to operator CN. Those nodes are referred to by Root Nodes (RN). The $(\mathcal{N} - \mathcal{R})$

remaining nodes are called Ordinary Nodes (ON). Each access network must have at least one RN to get connectivity to the operator network. All ONs are connected to operator network via one of the available RNs. An ON is directly aggregated either by a RN or by another ON, being one of its neighbors nodes. We consider there are at least two available technologies to ensure the backhauling of the considered network. Each linking technology is characterized by a capacity (Mbps), a range (m) and a cost (€). Each SC node has a traffic load generated by its attached users. Figure (2.1a) shows an example of a SCs network with three RNs and sixteen SCs.

The aim is to minimize issued cost of linking all network nodes and connecting them to the CN, while: i) fulfilling each node need of bandwidth; ii) respecting the capacities and ranges that available technologies allow. Actually, each ON must be aggregated by only one node using the cheapest technology satisfying those conditions: i) its range must cover the distance between considered node and its aggregator, and ii) its link capacity must be equal or greater than the traffic load handled by the node; this traffic load includes generated traffic by node end users devices and forwarded traffic load from nodes for whom it is the aggregator.

Consequently, the complexity of this cost minimization procedure rises from the choice of aggregation technology coupled with the choice of a unique aggregator node. For this reason, it is transcribed as an optimization problem. The objective of this problem is to minimize network backhauling cost while respecting above mentioned prerequisites. This problem is described in following subsection. Figure (2.1b) shows an expected linking solution for the network in Figure (2.1a) after solving the optimization problem.

2.2.1 Model description

The notations used for the optimization problem formulation are summarized in Table 2.1.

The problem consists in minimizing the costs generated by aggregating each node of the network to one of the RNs:

$$Minimize \sum_{\forall i \in \mathcal{N}-\mathcal{R}} \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{X}_{i,j}^{\ell} \times C_{i,j}^{\ell} \tag{2.1}$$

Subject to:

$$\forall i \in \mathcal{N} - \mathcal{R} : \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{X}^{\ell}_{i,j} = 1 \tag{2.2}$$

$$\forall i \in \mathcal{R} : \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{X}^{\ell}_{i,j} = 0 \tag{2.3}$$

$$\forall i \in \mathcal{N} - \mathcal{R} : \mathcal{C}_i = \lambda_i + \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{X}^{\ell}_{j,i} \mathcal{C}_j \tag{2.4}$$

$$\forall i \in \mathcal{N} - \mathcal{R} : \mathcal{B}_i = \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{X}^{\ell}_{i,j} \mathcal{T}^{\ell}_{i,j} \tag{2.5}$$

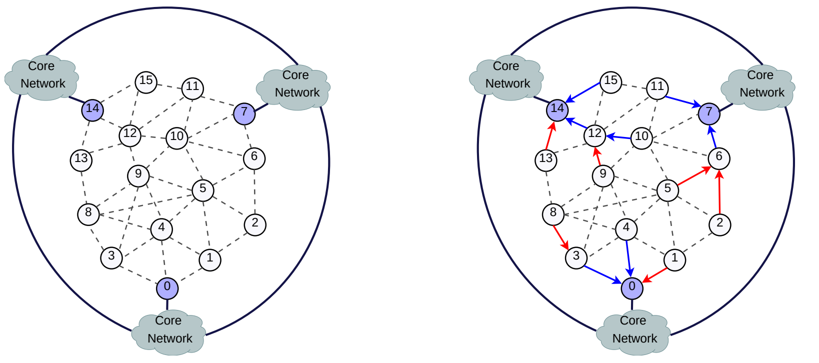
$$\forall i \in \mathcal{N} - \mathcal{R} : \mathcal{C}_i \leq \mathcal{B}_i \tag{2.6}$$

$$\sum_{\forall i \in \mathcal{R}} \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{F}^{\ell}_{j,i} = |\mathcal{N} - \mathcal{R}| \tag{2.7}$$

$$\forall i \in \mathcal{N} - \mathcal{R} : \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{F}^{\ell}_{i,j} - \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i), j \notin \mathcal{R}} \mathcal{F}^{\ell}_{j,i} = 1 \tag{2.8}$$

$$\forall i \in \mathcal{N} - \mathcal{R}, \forall \ell \in \mathcal{L}, \forall j \in \eta^{\ell}(i) : 0 \leq \mathcal{F}^{\ell}_{i,j} \leq (|\mathcal{N} - \mathcal{R}|) \times \mathcal{X}^{\ell}_{i,j} \tag{2.9}$$

Cost function (2.1) is the sum of aggregating technologies weighted by their respective costs. Each node, except RNs, is aggregated by only one node using one technology. Minimizing this function implies that each node is aggregated by the cheapest link ensuring capacity and range requirements. Constraint (2.2) expresses the aggregator



(a) (b)

Figure 2.1: A sixteen SCs network with three root nodes: (a) Initial network not linked, dashed lines are possible aggregations (b) A solution of linking SC nodes to the core network using two different technologies (blue and red arrows pointing to chosen aggregators)

Table 2.1: Notations used in formulating the optimization problem.

Notation	Description
$\mathcal{N}$	The set of all Small Cells nodes in the network.
$\mathcal{R}$	The set of nodes that have a connection with the core network, i.e. RNs.
$\mathcal{L}$	The set of technologies that can be used for backhauling network nodes.
$\mathcal{T}^{\ell}_{i,j}$	The bandwidth capacity between nodes i and j using the technology ℓ.
$\mathcal{X}^{\ell}_{i,j}$	Boolean decision variable. Equal to 1 if node i selects node j as parent using technology ℓ; 0 otherwise.
$C^{\ell}_{i,j}$	The cost of using technology ℓ between nodes i and j.
λ_i	The amount of traffic handled by node i.
$\mathcal{C}_i$	Amount of traffic that should be aggregated and forwarded by node i.
$\mathcal{B}_i$	Bandwidth required by node i to handle the amount of traffic.
$\eta^{\ell}(i)$	The neighbors of node i if the technology ℓ is used.
$F^{\ell}_{i,j}$	An integer variable that mimics packet flow in the network to ensure the connectivity between $\mathcal{N}-\mathcal{R}$ and $\mathcal{R}$, and prevent the creation of cycle.

uniqueness for ONs. Constraint (2.3) indicates that RNs are not aggregated by any node, since they are considered directly connected to the CN. Constraint (2.4) details the amount of traffic that an ON is carrying and should be forwarded to its parent; it is composed of: i) the generated traffic by users attached to this node, and ii) sum of traffic handled by all nodes aggregated by this node. Constraint (2.5) expresses the required bandwidth by an ON to its parent, i.e. the bandwidth capacity between the node and its parent using a specific linking technology. Constraint (2.6) specifies that the aggregated traffic by an ON should not exceed its required bandwidth to avoid congestion, i.e. chosen technology to aggregate this node should allow to carry all its aggregated traffic load. Constraint (2.7) states that the number of all flows arriving to all network RNs, whatever used technology is, corresponds exactly to $|\mathcal{N}-\mathcal{R}|$; this ensures that each ON is parented by one of the RNs (directly or indirectly). Constraint (2.8) indicates that, for each ON, the difference between the sum of packets flows to its neighbors and the sum of packet flows from its neighbor is equal to one. Constraint (2.9) points out that packet flow of node to one of its neighbors using a specific technology is either null (when the technology and/or the neighbor is not a parent) or has an integer value upper bounded by the number of maximum flows in the network $|\mathcal{N} - \mathcal{R}|$.

However, the above optimization problem, defined by equations (2.1) $\cdots$ (2.9), is not linear due to constraints defined by (2.4). It is a Mixed Integer Non-Linear Problem (MINLP). In order to simplify the solution, the following transformations are applied to (2.4). Thus, we convert the model to a linear problem. Constraint (2.4) is transformed to a linear constraint by adding a set of boolean variables $A^{\ell}_{i,j}$ to the optimization problem, where $i \in \mathcal{N} - \mathcal{R}$, $\ell \in \mathcal{L}$ and $j \in \eta^{\ell}(i)$. Additional constraints are added to the problem. Herein the transformed and added constraints:

$$\forall i \in \mathcal{N} - \mathcal{R} : \mathcal{C}_i = \lambda_i + \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{A}^{\ell}_{j,i} \tag{2.10}$$

$$\forall i \in \mathcal{N} - \mathcal{R}, \ell \in \mathcal{L}, j \in \eta^{\ell}(i) :$$

$$\mathcal{A}^{\ell}_{i,j} \leq \mathcal{C}_i \tag{2.11}$$

$$\mathcal{M}(1 - \mathcal{X}^{\ell}_{i,j}) + \mathcal{A}^{\ell}_{i,j} \geq \mathcal{C}_i \tag{2.12}$$

$$\mathcal{A}^{\ell}_{i,j} \leq \mathcal{M}\mathcal{X}^{\ell}_{i,j} \tag{2.13}$$

where $\mathcal{M}$ is a large number ($\mathcal{M} \to \infty$).

Actually, the terms $\mathcal{X}^{\ell}_{j,i}\mathcal{C}_j$ in equation (2.4) are replaced by the variables $A^{\ell}_{j,i}$. This means that if $\mathcal{X}^{\ell}_{j,i} = 1$, inequalities (2.11) and (2.12) lead to $A^{\ell}_{j,i} = \mathcal{C}_j$, and inequality (2.13) is satisfied; if $\mathcal{X}^{\ell}_{j,i} = 0$, inequality (2.13) leads to $A^{\ell}_{j,i} = 0$, and hence inequalities (2.11) and (2.12) are fulfilled. This ensures the equivalence between the non-linear and linear versions of this problem.

Based on the above analysis, the optimization problem is transformed to the following linear program; reformulated then to a Mixed Integer Linear Problem (MILP):

$$Minimize \sum_{\forall i \in \mathcal{N} - \mathcal{R}} \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{X}^{\ell}_{i,j} \times C^{\ell}_{i,j} \tag{2.14}$$

Subject to:

$$\forall i \in \mathcal{N}-\mathcal{R}: \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{X}_{i,j}^{\ell} = 1 \tag{2.15}$$

$$\forall i \in \mathcal{R}: \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{X}_{i,j}^{\ell} = 0 \tag{2.16}$$

$$\forall i \in \mathcal{N}-\mathcal{R}: \mathcal{C}_i = \lambda_i + \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{A}_{j,i}^{\ell} \tag{2.17}$$

$$\forall i \in \mathcal{N}-\mathcal{R}, \ell \in \mathcal{L}, j \in \eta^{\ell}(i): \mathcal{A}_{i,j}^{\ell} \leq \mathcal{C}_i \tag{2.18}$$

$$\forall i \in \mathcal{N}-\mathcal{R}, \ell \in \mathcal{L}, j \in \eta^{\ell}(i): \mathcal{M}(1-\mathcal{X}_{i,j}^{\ell}) + \mathcal{A}_{i,j}^{\ell} \geq \mathcal{C}_i \tag{2.19}$$

$$\forall i \in \mathcal{N}-\mathcal{R}, \ell \in \mathcal{L}, j \in \eta^{\ell}(i): \mathcal{A}_{i,j}^{\ell} \leq \mathcal{M}\mathcal{X}_{i,j}^{\ell} \tag{2.20}$$

$$\forall i \in \mathcal{N}-\mathcal{R}: \mathcal{B}_i = \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{X}_{i,j}^{\ell} \mathcal{T}_{i,j}^{\ell} \tag{2.21}$$

$$\forall i \in \mathcal{N}-\mathcal{R}: \mathcal{C}_i \leq \mathcal{B}_i \tag{2.22}$$

$$\sum_{\forall i \in \mathcal{R}} \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{F}_{j,i}^{\ell} = |\mathcal{N}-\mathcal{R}| \tag{2.23}$$

$$\forall i \in \mathcal{N}-\mathcal{R}: \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i)} \mathcal{F}_{i,j}^{\ell} - \sum_{\forall \ell \in \mathcal{L}} \sum_{\forall j \in \eta^{\ell}(i), j \notin \mathcal{R}} \mathcal{F}_{j,i}^{\ell} = 1 \tag{2.24}$$

$$\forall i \in \mathcal{N}-\mathcal{R}, \forall \ell \in \mathcal{L}, \forall j \in \eta^{\ell}(i): 0 \leq \mathcal{F}_{i,j}^{\ell} \leq (|\mathcal{N}-\mathcal{R}|) \times \mathcal{X}_{i,j}^{\ell} \tag{2.25}$$

2.2.2 Performance Analysis

In this section, we evaluate backhauling problem for wired and wireless backhaul network. This means that cost analysis is made for a network fully connected with wired technologies or with wireless ones. Analysis is done for many surfaces, traffic demands and operator presence. The problem is solved using Gurobi Optimizer software.

2.2.2.1 Evaluation method

The service area, i.e. network coverage area, is considered to have a square form. SCs coverage areas have hexagonal shape. Random geographic SCs coordinates are generated following a random uniform distribution within network area. We assume that all links would achieve line-of-sight (LOS). The same network area may be covered by variable number of nodes depending on their ranges; the wider ranges are, the smaller number of needed nodes becomes. Number of needed SCs is computed as the rounded ratio of network area to single node area. Number of RNs may be configured as needed by setting at least one RN for each network. Initially, SCs are randomly affected a traffic load in a predefined interval.

Before computing the optimal linking that satisfies minimal linking cost, neighbors of each node using a specific technology are identified. A node i is a neighbor of node j using technology ℓ iff the Euclidean distance between the two nodes doesn't exceed technology range.

For the simulations, we consider two sets of technologies: i) wired based on fiber optic, and ii) wireless based on Microwave (MW) and most recent IEEE 802.11. The characteristics of those technologies are detailed in table (2.2).

Table 2.2: Linking Technologies Characteristics.

Technology	**Capacity (Mbps)**	**Range (m)**	**Cost (€)**
Optical-Ethernet1	100	80000	25000
Optical-Ethernet2	1000	10000	25000
Optical-Ethernet3	10000	10000	25000
GPON	2480	20000	25000
MW Standard 6-42GHz	400	35000	5000
MW V-band	1250	2000	5000
MW E-band	1200	5000	5000
802.11n	450	250	1400
802.11ac	1300	180	1300

2.2.2.2 Simulation results

Here we analyze some network specifications impact on issued cost for both cases: wired and wireless backhauls.

Figure (2.2) represents bakchauling cost as a function of the surface area to be covered, for wired (Figure (2.2a)) and wireless (Figure (2.2b)) backhauls. Figure (2.2c) shows both wired and wireless backhaul costs. We consider that the targeted area is covered by 500m range SCs (Micro Cells). Plots for different values of fixed

SC traffic loads are represented. The first observation is that for the same network area, wireless technologies generate lower costs than wired ones, as shown in Figure (2.2c).

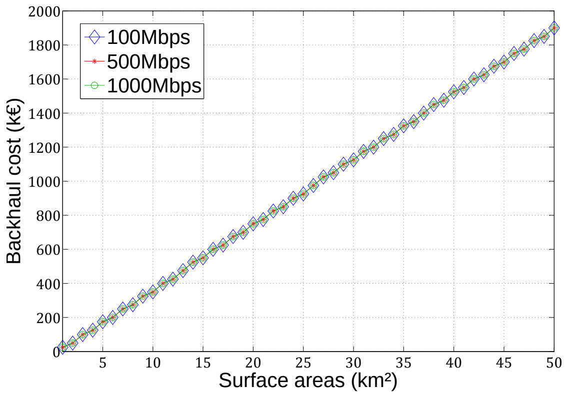
Both generated costs by full wired and full wireless backhauls are increasing as the surface area increases. However, wired backhaul cost is increasing dramatically, whereas wireless backhaul cost progresses following a gentle slope. For example, for a surface area of $50km^2$ the backhaul cost is more than 1900k€, while it does not exceed 350k€ for the wireless backhaul. This means if the network is becoming wider, backhauling it using wireless links is economically more advantageous.

For a SCs network loaded with different amounts of traffic, the linking cost is the same when using wired technologies, whereas it is fairly steady for wireless backhaul. This is due to very high link capacities of studied wired connections. Those high capacities largely satisfies network needs in terms of bandwidth, but at a certain high cost. In the contrary, wireless technologies capacities fit almost exactly network bandwidth requirements. For this reason wireless connections cost increases, but slowly, when traffic flows augment. This is encouraging operators to invest on wireless backhaul.

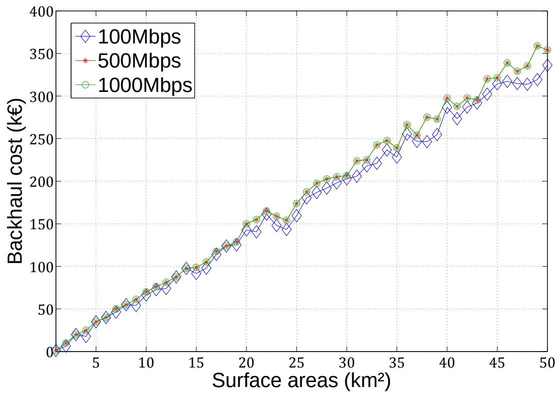
To analyze deeply the impact of each SC traffic load on linking cost, Figure (2.3) shows backhauling cost evolution as a function of the average amount of traffic generated by each SC node users, for two network sizes: $9km^2$ (Figure (2.3a) and Figure (2.3b)) and $25km^2$ (Figure (2.3c) and Figure (2.3d)). Plots for different number of used SCs (and consequently SC ranges) are included. We observe a quasi-constant cost when SC traffic flow increases. This corroborates previous observation on Figure (2.2). Average traffic load growth does not impact wired linking cost, while it barely impacts wireless one. The latter never reaches wired configuration cost for the same use case. This proves that wireless backhaul is more profitable.

When the network is covered by a higher number of SCs (Smaller SCs ranges), it costs more to connect all these nodes to the CN, and vice versa for both sets of technologies. Actually, the larger the number of nodes to link is, the higher number of needed links becomes. As we assumed that each node must be aggregated by one node, each of the ONs requires one link; there are $|\mathcal{N} - \mathcal{R}|$ necessary links. If $\mathcal{R}$ is fixed to one, the increase of $\mathcal{N}$ generates higher costs. Higher nodes instances correspond to smaller nodes ranges; then it is recommended to invest in SCs with larger ranges in order to achieve minimal connection cost.

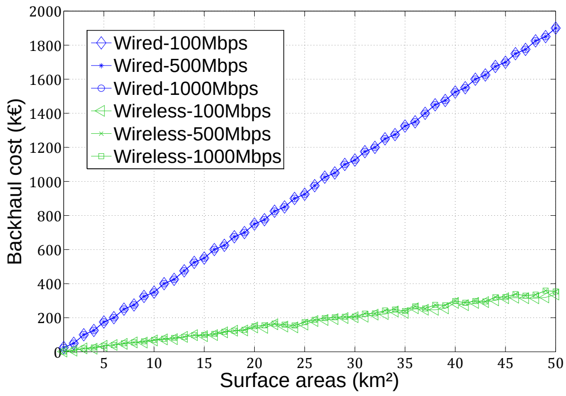
For wireless backhaul (Figure (2.3b) and Figure (2.3d)), there is a small increase of



(a) Wired Backhaul only



(b) Wireless Backhaul only

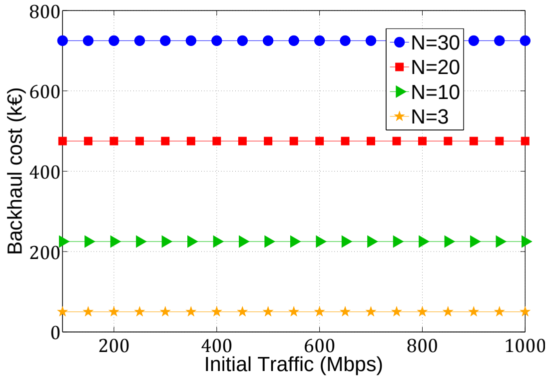


(c) Wired and Wireless Backhauls

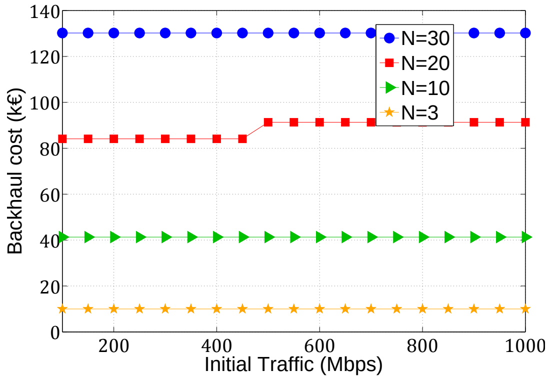
Figure 2.2: Generated costs versus surface areas (km^2)

backhaul cost in the initial traffic interval of [450, 500] when $N = 20$. This shows that the optimization model adjusts the solution depending on initial traffic growth. However, the backhaul cost remains almost stable in the same traffic interval for other values of N. Indeed for those network sizes, a wide range of network needs in terms of traffic are satisfied.

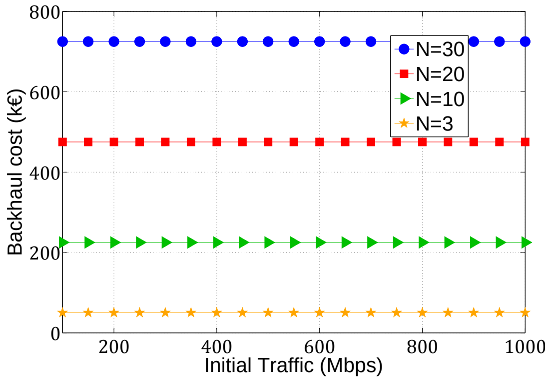
Figure (2.4) depicts network linking cost as a function of the ratio of RNs in the network for two surface areas: $9km^2$ (Figure (2.4a) and Figure (2.4b)) and $25km^2$ (Figure (2.4c) and Figure (2.4d)). Plots of random traffic loads of SCs are considered. Random traffic loads are within three intervals: [100Mbps, 200Mbps], [100Mbps, 500Mbps] and [100Mbps, 700Mbps]. Generated backhauling cost is decreasing when the network has more RNs. Actually, the more available the RNs are, the fewer the



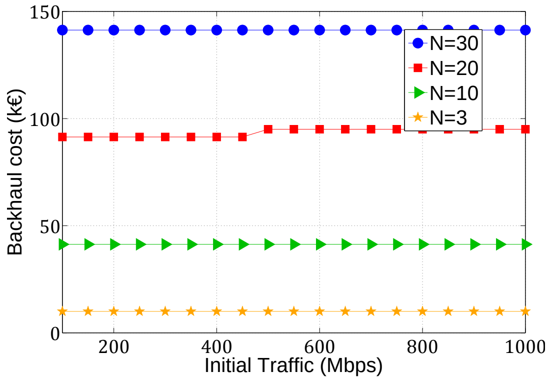
(a) $9km^2$/Wired Backhaul



(b) $9km^2$/Wireless Backhaul



(c) $25km^2$/Wired Backhaul

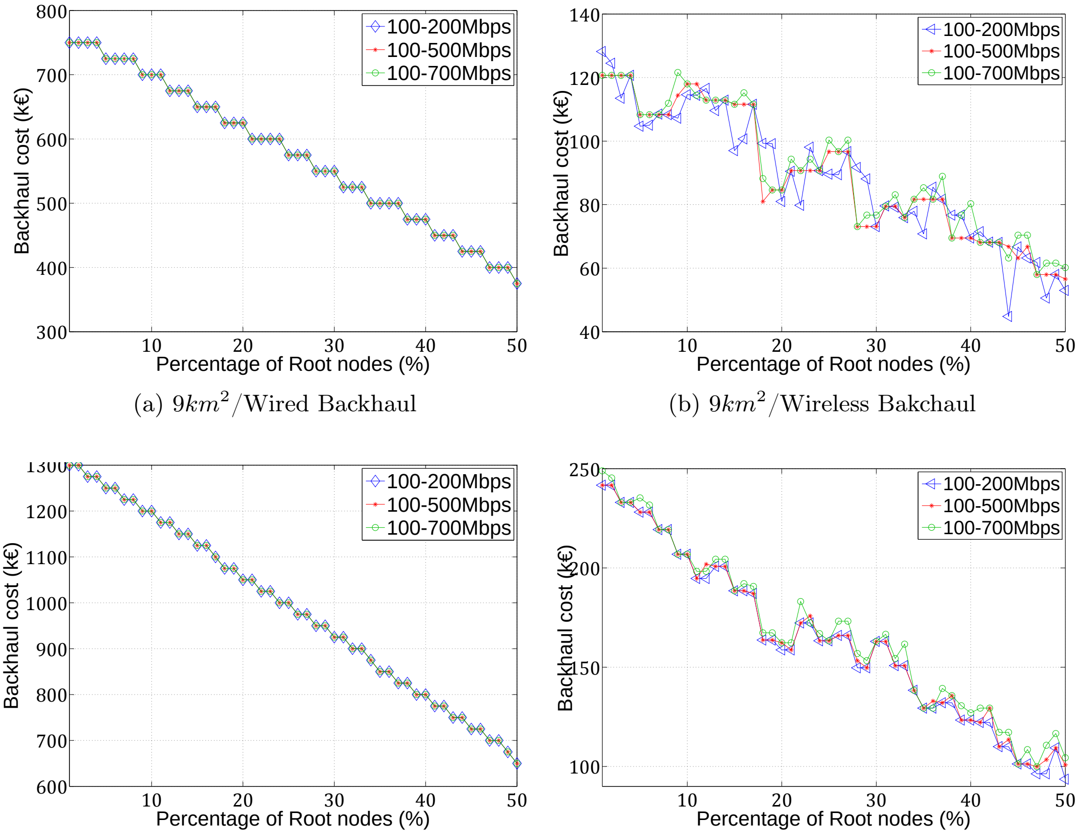


(d) $25km^2$/Wireless Backhaul

Figure 2.3: Generated cost versus initial traffic for each node (Mbps)

nodes to link are and thus the fewer the links to deploy are. This reduces directly linking costs.

When the number of RNs increases, wired backhaul cost drops significantly, however wireless backhaul cost decreases smoothly. This means that wireless backhaul cost is less sensitive to the availability of operator CN PoCs. Instead of investing in most intelligent and powerful nodes like gateways, the operator has the possibility to reduce this investment by deploying more wireless linking technologies at attractive costs. Reducing the number of gateways is advantageous for two mean reasons: 1) those high processing nodes costs important CAPEX and OPEX, and 2) gateways must be connected to other CN nodes at high rates technologies; this could not be done without wired technologies (especially fiber), thus reducing gateways implies reducing those additional costs.



(a) $9km^2$/Wired Backhaul

(b) $9km^2$/Wireless Bakchaul

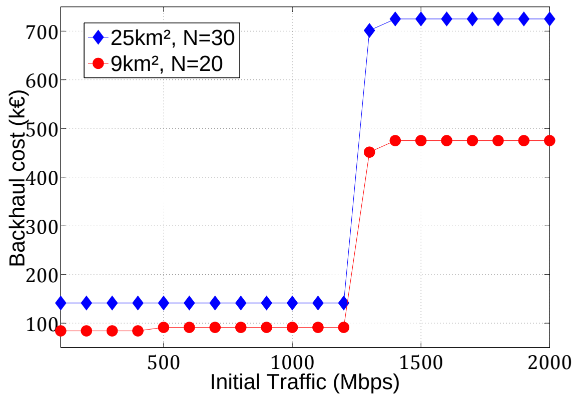
(c) $25km^2$/Wired Backhaul

(d) $25km^2$/Wireless Backhaul

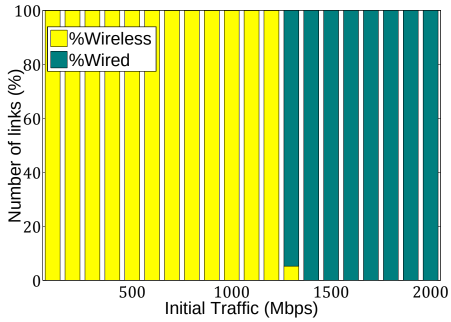
Figure 2.4: Generated cost versus percentage of root nodes

For the ranging traffic loads, wired backhaul cost is exactly the same for the three intervals, but wireless backhaul cost is slightly fluctuating. Practically, random traffic values, within considered intervals, are randomly allotted to SC nodes, so the aggregated traffic flow in each node is different in each traffic range simulation. Since wired technologies have high capacities, the same type of link is chosen to link a node to another, and hence the cost of the link is the same; it does not impact overall connection cost. Nevertheless, wireless technologies have lower capacities, so for the same initial topology, two arbitrary nodes are not necessarily connected using the same technology for all traffic ranges. This explains the observed fluctuations on linking costs. As those variations don't create cost gaps, it sustains the adoption of wirless multi-technology backhaul.

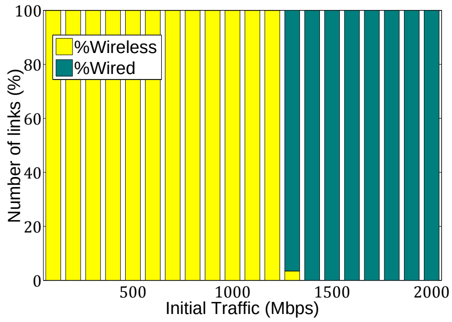
Figure (2.5) gives some results when allowing both wired and wireless links for back-



(a) Mixed Backhaul Cost



(b) % of links types: $9km^2$



(c) % of links types: $25km^2$

Figure 2.5: Mixed Backhaul characteristics versus Initial Traffic (Mbps)

haul design. Figure (2.5a) shows cost evolution for two network sizes, each having one RN, for different initial traffic flows. Figure (2.5b) and (2.5c) reveal usage percentage of using wireless/wired links for the two networks. There is a sudden linking cost increase for traffic loads above 1.2Gbps. Referring to Figure (2.5b) and (2.5c), it is due the use of more wired links in the backhaul. Actually, as initial traffic increases, wireless links are no more capable of carrying it, wired links are chosen instead. As introduced in table 2.3, the best wireless link capacity is 1.25Gbps; this is why the sudden increase is observed for 1.2Gbps. As a consequence, issued costs explode beyond this traffic. Those results point out wireless backhaul benefit over the wired one, even for highly loaded network.

2.3 Use cases study

In this section, the wireless aggregation schemes of three networks are discussed when using two mean methods: 1) the above proposed optimization program and 2) a greedy heuristic algorithm. Unlike the the optimization program, the heuristic function adds constraints on possible aggregators for each node. Actually, a node has one or two candidates parents. Below, the considered topologies are described then their linking solutions are compared for the optimization and heuristic methods.

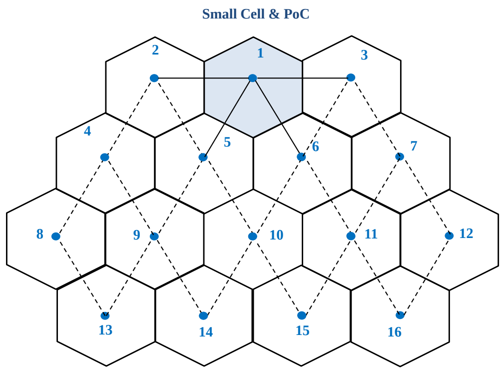
2.3.1 Considered topologies

Three access networks are considered to depict the foretasted deployments in green-field deployments. Those use cases are designed depending on three parameters: 1) population (number of inhabitants), 2) potential subscribers density and 3) surface area to cover. Figure (2.6) shows the considered use cases.

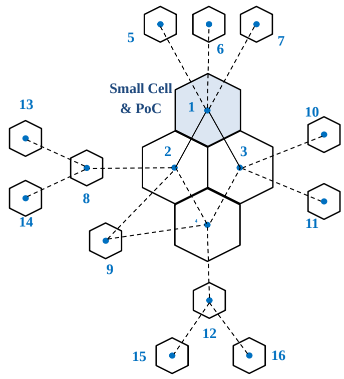
- *Highly dense wide area* (Use case 1): this case is chosen to depict a strong need to efficient and important mobile broadband service supplying (relatively medium-small city). It is represented by a set of SCs (Namely Micro Cells) which are solidly connected. The PoC node is included in the topology on one SC node and is then the only root node of this network.

- *Low dense wide area* (Use case 2): this use case is considered to describe a less demanding area to be covered, in terms of need to mobile broadband services (small city with its agglomerations). This topology is figured by a set of SCs nodes (Pico and Micro cells) connected sparsely with each other, with a centered compact zone. The central compact part of the topology refers to a city downtown (i.e. most populated part or central host of economic activities). The PoC is considered to be combined with one SC and to be the aggregator of all nodes traffic, i.e. the RN of the network.

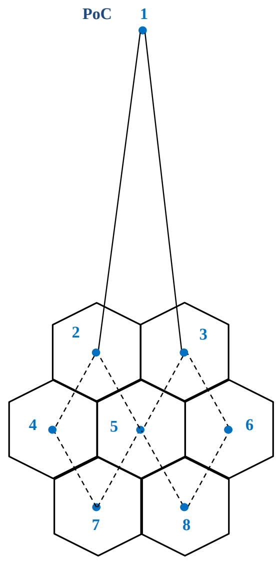
- *Isolated small area* (Use case 3): this use case has been regarded as it reflects many real cases in low density and rural areas that need targeted services. A spot of solidly connected SCs (Pico or Micro Cells) is designed to picture this use case. The small area is considered to be 30-50km far from the closest PoC (i.e. RN).



(a) Use case 1: Highly dense wide area



(b) Use case 2: Low dense wide area



(c) Use case 3: Isolated small area

Figure 2.6: Considered Access Small Cells based Network topologies

2.3.2 Greedy heuristic algorithm

The above proposed optimization problem gives cost-optimal solution for backhauling SCs set, but the chosen aggregator for a specific SC is not always the geographically closest parent. It is due to high ranges of some of the considered technologies (namely Standard-6-42-GHz) and fixed costs per link (instead of costs per distance unit). To address this complexity, a novel heuristic is proposed.

In this heuristic algorithm, nodes are classified into a hierarchy regarding their distance from RN (i.e. PoC). The farther the node is from RN, the fewer users' traffic that would be carried, the easier would be the decision of linking technology. Nodes are then allocated one or two candidates aggregators in their upper hierarchy level respectively; depending on closest aggregators in terms of Euclidean distance. The algorithm starts the decision of linking technologies from down to upper access network (from farthest to closest nodes to PoC). Aggregator links are affected to farthest nodes, depending on traffic to carry out to CN, and respecting the cost minimization by choosing cheapest linking technology. The new load of each new defined aggregator is updated taking into consideration aggregated nodes traffic. The same step is repeated until upper node is reached. We refer to this algorithm by "Heuristic 1". Figure (2.7) shows the flow chart of this heuristic. In case one node at least could not be aggregated to an upper node because its load is higher than available linking technologies capacities, we consider that the algorithm fails to get a complete solution for the studied topology.

For cases in which this first version of heuristic does not give a global solution, two other heuristics are defined. The devised heuristics are based on current heuristic principle, but they relieve it by using two different policies: 'Link Doubling' or 'Access Control':

a. Heuristic with Link Doubling (LD) policy: wherever first defined heuristic algorithm fails to allocate suitable linking technologies, a couple of links is used to carry concerned node load. Links may belong to the same or different linking technologies. As it is indicated by its nomination, this heuristic allows only two links maximum between two nodes. Obviously, this operation will increase total cost of linking. This heuristic is referred by "Heuristic 2 LD".

b. Heuristic with Access Control (AC) policy: this heuristic limits aggregated traffic by each node by dropping a percentage of it and allowing carrying the rest to upper node. This operation limits bandwidth and excludes some clients since their traffic could be dropped. This heuristic is called "Heuristic 2 AC".

2.3.3 Results comparison

In this subsection, wireless backhauling solutions from optimization program and heuristics are discussed for the three networks use cases described in 2.3.1. The dashed lines in Figure (2.6) represents the candidates aggregators limitations, in-

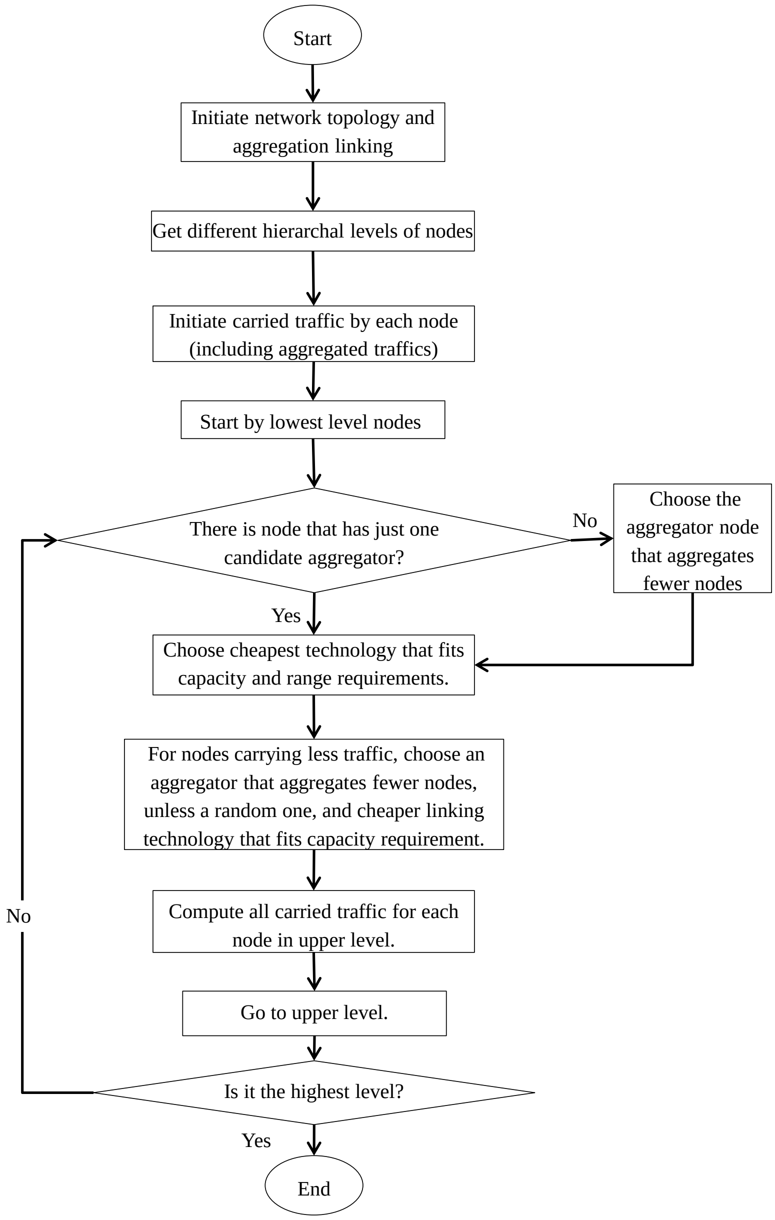


Figure 2.7: Heuristic 1 Flow Chart

troduced by heuristic algorithms. Topologies characteristics are presented in Table 2.3.

Table 2.3: Characteristics of considered use cases topologies

Use Case	Highly dense wide area	Low dense wide area	Isolated small area
Surface Area (km^2)	100	50	9
SC type	Micro	Micro & Pico	Micro
SC radius (km)	1.5	1 & 0.2	0.7
Nb. SCs	16	4 & 12	7
Comments			30km from RN

2.3.3.1 Backhaul costs comparison

Herein, generated backhaul costs using optimization and heuristics methods are compared for different networks loads. Figure (2.8) represents the evolution of those costs as a function of initial node traffic for the three network cases. The access control percentage used for "Heuristic 2 AC" is 10%.

As observed, both optimization method and heuristics gives aggregation solutions at the same costs apart from "Heuristic 2 LD". Actually for the first use case (Figure (2.8a), the minimum distance between a node and its closest neighbor is 2.598km; by referring to table 2.3, only two wireless technologies can fit this range: *Standard-6-42-GHz* and *E-Band*. Since those technologies links costs the same, there is no difference between backhaul costs, even if the proposed aggregators solutions are not the same for optimization model and heuristics. For use case *2*, the minimum distance that separates a node to its closest neighbor ranges from 497m to 2.219km: three wireless technologies are left to link this network; and all of them have the same cost. The same observation is done for use case *3* with a minimum distance of 1.212km. The considered characteristics of the three networks yield to identical costs results but will more likely implies different linking solutions (2.3.3.2).

Heuristic 2 LD produces higher costs compared with other methods from the point *Heuristic 1* fails to give a solution; the extra cost is due to added links by doubling policy. *Heuristic 2 LD* does not allow a profitable alternative.

Another important finding from Figure (2.8): heuristic algorithms fails to link the considered networks for lower values of initial traffic while the optimization program gives solutions at higher traffic: 1180Mbps for use case *1*, 1220Mbps for use case *2* and 400Mbps use case *3*. *Heuristic 2 LD* has better results than the basic *Heuristic 1* and *Heuristic 2 AC*, but still does not reach the performance of the optimization model. This is due to two assumptions made in heuristic algorithms: 1) a node has at most two candidate aggregators and 2) the aggreagtor is chosen, then the linking technology is decided. Hence, when the load of a node can not be carried by any of available links for the chosen aggregator, the algorithms are less useful in loaded networks.

2.3.3.2 Backhaul solutions

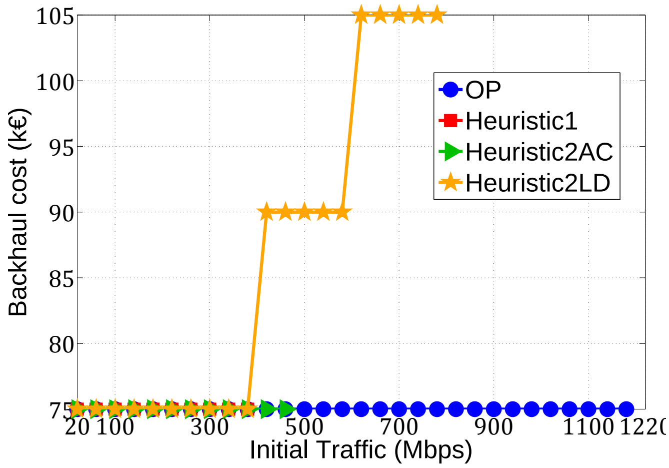
In this subsection, wireless aggregation solutions using both optimization and heuristic methods for a specific initial traffic are explored. The considered initial traffic corresponds to the highest traffic for which all methods give solutions. Table 2.4, Table 2.5 and Table 2.6 show the linking solution using optimization problem and heuristic algorithm: the three heuristics methods gives the same linking solution. The three considered networks are linked differently by optimization method and heuristic algorithm, even if the generated cost is the same. Heuristic function sorts networks nodes into hierarchy levels depending on their distance from the PoC and allow maximum of two candidates aggregators to each nodes: heuristic allows to choose the geographically closest aggregator. However, there is no such constraint in the optimization model; the latter targets a global cost function minimization, and hence allocates aggregator to node depending even if this aggregator is geographically far. For example in the first use case, node 3 is aggregated by node 1 using optimization program while it is aggregated by node 1 with heuristic. The used linking technologies are also different: a link to a close aggregator requires lower range than a link to a farther aggregator.

2.3.4 Summary

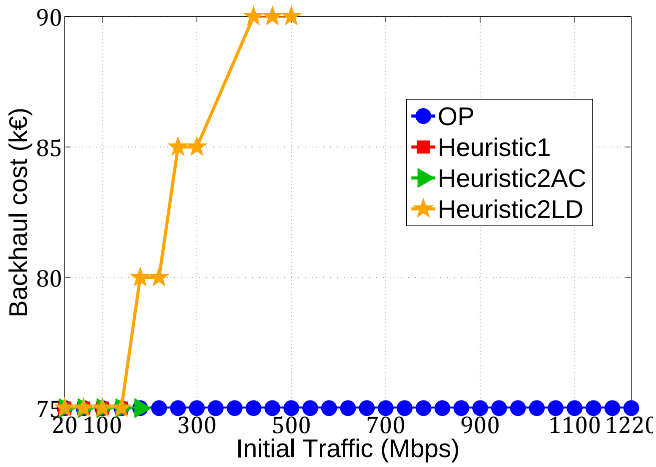
In real networks deployments, it is more reliable to use short rather than long links to bakchaul a network using wireless technologies. For example, microwave links would require more repeaters at long distances, especially in Non-Line-of-Sight (NLOS) areas; moreover those repeaters are more expensive.A distance constraint may be added to the optimization problem in order to foster the aggregation decision for close aggregators. Actually, this distance dimension can be inserted by considering a cost per unit distance instead of cost per link. This would yield also to give more accurate backhauling costs, and hence compare the advantages and limitations of each aggregation method.

Table 2.4: Topology Aggregation solution using OP and Heuristic for highly dense wide area (Initial Traffic = 400 Mbps)

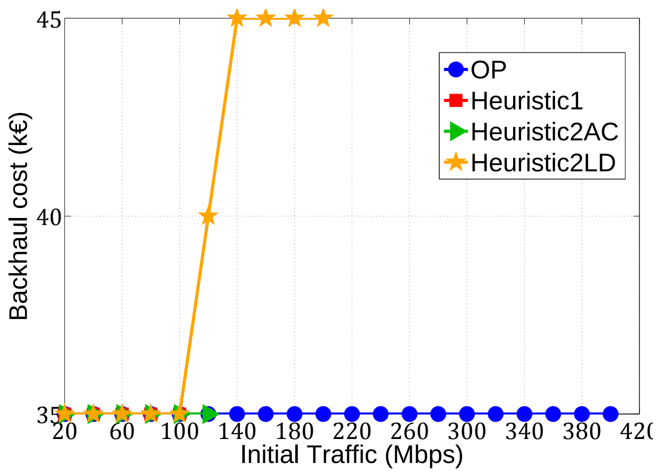
	Optimization Problem		Heuristic	
Node ID	Aggregator ID	Aggregation Technology	Aggregator ID	Aggregation Technology
1	Nan	Nan	Nan	Nan
2	3	Standard-6-42-GHz	1	E-band
3	4	Standard-6-42-GHz	1	E-band
4	8	Standard-6-42-GHz	2	E-band
5	14	E-band	1	E-band
6	4	Standard-6-42-GHz	1	E-band
7	9	Standard-6-42-GHz	3	E-band
8	1	Standard-6-42-GHz	4	Standard-6-42-GHz
9	14	E-band	5	Standard-6-42-GHz
10	3	Standard-6-42-GHz	6	E-band
11	10	E-band	7	E-band
12	10	Standard-6-42-GHz	7	Standard-6-42-GHz
13	14	E-band	8	Standard-6-42-GHz
14	11	Standard-6-42-GHz	10	Standard-6-42-GHz
15	13	Standard-6-42-GHz	11	Standard-6-42-GHz
16	14	Standard-6-42-GHz	12	Standard-6-42-GHz



(a) Use case 1: Highly dense wide area



(b) Use case 2: Low dense wide area



(c) Use case 3: Isolated small area

Figure 2.8: Generated Backhaul costs versus the initial traffic for the three topologies

Table 2.5: Topology Aggregation solution using OP and Heuristic for low dense wide area (Initial Traffic = 150 Mbps)

	Optimization Problem		Heuristic	
Node ID	Aggregator ID	Aggregation Technology	Aggregator ID	Aggregation Technology
1	Nan	Nan	Nan	Nan
2	3	Standard-6-42-GHz	1	V-band
3	5	Standard-6-42-GHz	1	V-band
4	3	Standard-6-42-GHz	3	V-band
5	10	E-band	1	Standard-6-42-GHz
6	2	Standard-6-42-GHz	1	Standard-6-42-GHz
7	2	Standard-6-42-GHz	1	Standard-6-42-GHz
8	2	Standard-6-42-GHz	2	V-band
9	10	E-band	4	Standard-6-42-GHz
10	16	Standard-6-42-GHz	3	Standard-6-42-GHz
11	12	Standard-6-42-GHz	3	Standard-6-42-GHz
12	15	V-band	4	V-band
13	1	E-band	8	Standard-6-42-GHz
14	5	Standard-6-42-GHz	8	Standard-6-42-GHz
15	6	Standard-6-42-GHz	12	Standard-6-42-GHz
16	13	E-band	12	Standard-6-42-GHz

Table 2.6: Topology Aggregation solution using OP and Heuristic for isolated small area (Initial Traffic = 100 Mbps)

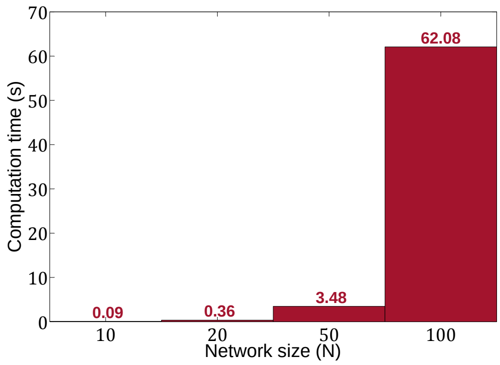
	Optimization Problem		Heuristic	
Node ID	Aggregator ID	Aggregation Technology	Aggregator ID	Aggregation Technology
1	Nan	Nan	Nan	Nan
2	8	E-band	1	Standard-6-42-GHz
3	2	V-band	1	Standard-6-42-GHz
4	1	Standard-6-42-GHz	2	Standard-6-42-GHz
5	3	Standard-6-42-GHz	3	Standard-6-42-GHz
6	5	Standard-6-42-GHz	3	Standard-6-42-GHz
7	4	E-band	4	Standard-6-42-GHz
8	7	Standard-6-42-GHz	6	Standard-6-42-GHz

2.4 Practical aspects discussion

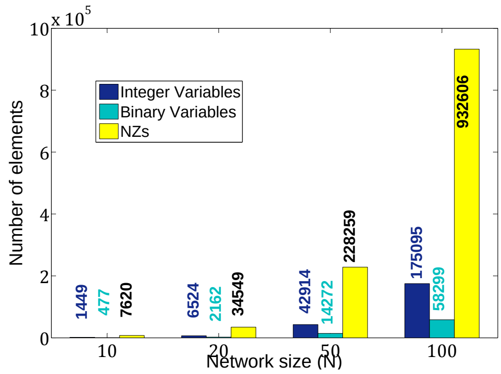
As introduced in subsection 2.2.1, the initially proposed MINLP is reformulated to a MILP by using linearization transformation. It is linearized to perform a simulation and stability analysis. The obtained MILP problem consists of a linear objective function, a set of linear equalities and inequalities constraints and a set of variables with integer restrictions. The MILP problem is solved using a linear programming based on branch-and-bound algorithm. The principle of this approach is to relax the MILP to a Linear Program (LP) and solve this new version. Since it is unlikely that the solution satisfies removed integrality restrictions of the MILP, some integrality constraints are added step by step. Actually, an integer restricted variable in the original MILP whose value was found fractional in the LP, is restricted under two constraints that can not be jointly satisfied: two new MILP problems are then defined for this variable. This variable is called a *branching variable*. The two sub-MILPs are relaxed to LPs then solved. The one who gives the best optimal solution replaces the original MILP. The same idea is repeated and a *search tree* is generated. This *tree* is made up of *nodes*, which are generated MILPs. The *root node* is the original MILP. The more integer variables has the MILP, the more *nodes* has the *search tree*; as a consequence, the number of integer variables influences the running time of the algorithm in a branch-and-bound approach.

The number of proposed MILP variables depends on the number of ON nodes, number of RN nodes and number of considered linking technologies. For high instances of those parameters, the problem can not be solved or consumes high computing times and resources. This is because it is NP-hard. Indeed, this MILP may be reduced to a NP-complete problem: it is Degree-constrained Minimum Spanning Tree (DCMST). An input topology is equivalent to weighted undirected graph with $\mathcal{N}$ nodes (i.e. SC nodes) and linking technologies are edges weighted by their costs. Number of node connections is analogous to node degree in DCMST. In this MILP, a node has $\mathcal{N}$ connections maximum (unique aggregator and $\mathcal{N}-1$ aggregated nodes maximum). Thus the question to answer is "Does the topology have a spanning tree in which no node has degree greater than $\mathcal{N}$".

Figure 2.9 shows the computational complexity measurements as a function of the network size $\mathcal{N}$. The computation time increases as the network size increases as shown in Figure (2.9a). More specifically, when the networks expands, the number of interger variables, including binary ones, and non-zero (NZ) elements increases as



(a) Computational Time



(b) Nb of Solving Elements

Figure 2.9: Optimal solution computational complexity measurements

noted in Figure (2.9b). The increase of $\mathcal{N}$ implies the increase of the number of links to set (including both aggregator choice and technology decision). Hence it increases the number of combinaisons of feasible solutions when solving the problem. However, the computation time remains advantageous for network size up to $\mathcal{N} = 100$ with about one minute. In fact, this MILP can be applied for designing the backhaul of quite large networks. For larger networks, whose sizes are above 110 SCs, the computation time becomes consequent: e.g. 2025s for $\mathcal{N} = 130$.

To address this computational complexity, there are many practical methods to find good enough solutions in reasonable time. In the proposed MILP, the program identifies the neighboring nodes to each node when using each of the available technologies. Hence it is recommended to delete the variables $\mathcal{X}_{i,j}^{\ell}$ who will not be part of the solutions, i.e. excluding non-neighboring nodes.

Another method is to increase the gap percentage to the optimal solution. The solver uses the duality-gap method to find an upper bound for the optimality of the best solution found so far. During solving process, the solver records the highest lower bound found and compares it with the best MIP solution found. Forcing the solver to null gap percentage means to direct it to find **The** optimal solution; using a greater gap percentage relaxes the solution. An non-null x% gap means that the solver considers solutions no more worst than x% of the optimal solution is an acceptable solution. This can save significant processing time.

There are also heuristic methods that can be used for reducing processing time. Heuristic algorithms can be used to speed up the process of finding a sufficient but not necessarily optimal solution. In cases it becomes more complex to compute MILP solutions, it is necessary to make a trade-off between the quality of the solution and the processing costs. For the proposed MILP, heuristic algorithms based on Genetic and Ant-Based algorithms can be proposed to solve it in polynomial time.

2.5 Conclusion

In this chapter, we address the problem of selecting most cost-efficient technologies that ensure backhaul connectivity for a SCN in green field deployment. For this purpose, we have proposed a novel cost optimization problem that aims at reducing backhauling cost of a network while respecting constraints dictated by linking technologies characteristics and network traffic.

Implementation results are discussed for two sets of connection technologies: wired and wireless. Obtained results on cost evolution, which depend on some network features (size, traffic load and operator presence), corroborate the benefit of wireless backhaul. Not only wireless connections to the CN costs less than wired ones, but also have a small cost derivative function when the network becomes wider, is highly loaded or has limited access to CN. This is making wireless multi-technology backhaul an attractive solution for green-field SCNs, especially for long term deployments where the SCNs are expected to grow and become greedier regarding broadband services. The results sustain insightful guidelines on planning SCs backhaul for MNOs. It jointly considers economic and service needs requirements.

The comparison of proposed MILP and heuristic algorithm solutions for particular use cases topologies showed how the MILP solutions do not consider any geographical constraint when making aggregation decision in contrast to heuristics; however, the latter fails to give backhaul solutions in highly loaded networks.

The MILP can deliver optimal linking solutions at reasonable time for quite large size networks (about 100 nodes). The processing time becomes more substantial for wider networks. The targeted service areas will not need that number of SCs to be fully covered. Unless the operator foresees a multi-areas planning, the MILP gives the best solutions.

Chapter 3

Small Cells Network Planning based on Traffic Analysis

Contents

3.1 Introduction

There are some limitations affecting wireless backhaul infrastructure compared to wired ones (such as Fiber or cable); one of the most crucial is low data rates. The SCs backhaul pipline must be able to transport end users traffic flows in both directions (uplink and downlink) at a minimum of Quality of Service (QoS). SCs backhaul should be planned cleverly to deploy the most adapted wireless links. On the one hand, connections between access nodes -i.e. SCs- and closest operator Core Network (CN) node may require more capacity and higher ranges since CN gateway might be quiet far. On the other hand, mutual connections between SCs may need faster links with less bandwidth. Users equipments (UEs) drive those choices by the throughput each one generates. Consequently, how UEs throughput effect on SC interfaces connecting to its gateway and to other SCs could be quantified?

In this chapter, we want to assess the influence of end users devices activity on carried traffic by access nodes, i.e. the small cells. We target a full SCs access network deployment; those SCs would be wirelessly backhauled to the closest CN node. We want to analyze a SC generated traffic in order to choose the most suitable wireless links in terms of capacities. To fill this gap, we quantify throughput generated on a SC interfaces by its UEs. The cellular system is modeled as a Markov chain that takes into account UEs activity. The aim of this model is to evaluate UE activity effect on SC logical interfaces traffic flows. An UE throughput is split into user and control planes flows. UE throughput is an average value for many end users. It may refer to whether uplink or downlink throughputs. It may indicate whether mean busy hours or peak quiet hours throughputs.

The remaining of this chapter is organized as follows. Section 3.2 gives an overview of cellular access network dimensioning, especially for LTE networks. Section 3.3 depicts an analysis of a cellular backhaul traffic and its classification to parts depending on whether it is user or control traffic, and whether it goes throughout S1 or X2 small cell interface. Section 3.4 describes the Markov model we propose to assess end users devices activity impact on a SC traffic going either by its S1 or X2 interface. Section 3.5 discusses most relevant computed results obtained by the Markov model: it includes primarily generated traffic on S1 and X2 as a function of system parameters. Section 3.6 summarizes this chapter.

3.2 Access network dimensioning

3.2.1 General description

LTE network planning is performed following a specific process. This process is made up of three major phases [50]-[64]-[65]-[45]-[52]:

1. **Dimensioning**: it represents the initial phase of network planning. Its purpose is to estimate the required base stations features to meet traffic load needs in service area. It consists on identifying targeted service area requirements in terms of traffic needs, transport links, etc. It allows then to define strategies for coverage, capacity and quality of the service. A set of input parameters are used by dimensioning process; obtained results are effective only for the considered parameters values. These parameters are primarily subscribers population, traffic distribution, geographical area characteristics, frequency band, allocated bandwidth and coverage and capacity requirements. Dimensioning uses relatively simple models compared to detailed planning process. However, dimensioning models should offer enough accurate results to determine accurate traffic profiles. Dimensioning is based on four main elements: Data/Traffic Analysis, coverage estimation, capacity evaluation and transport dimensioning.

2. **Core (Detailed) Planning**: This phase focuses on coverage planning including site selection and acquisition, and fulfilling capacity requirements. The output of this phase is planning parameters for the targeted area. Actually, a coverage estimation is performed in order to determine the coverage area of each base station. It consists on computing the maximum range reached by base station, where end users can hear the base station signal. In the coverage area, receivers can detect the base station but not necessarily establish an acceptable connection (e.g. voice call). Coverage planning is based on radio link budget and coverage analysis. Radio link budget computes gains and losses affecting the signal in the path from the base station to the end user. Many parameters effect those gains/losses like frequency and antenna diversity. The analysis of the radio link budget results allows to obtain the maximum allowed propagation loss. It refers to the maximum tolerated loss of the signal when traveling from the base station transmitter to the end user receiver. The maximum allowed propagation loss is converted to a distance using specific propagation models; this distance represents the radius of the

cell used to compute the number of required sites.

Capacity planning refers to network ability to ensure services to end users at a certain level of quality. After the coverage planning is performed, capacity requirements are analyzed. It includes selection of site and system configuration (used channels, channel elements and sectors). System configuration is realized to meet traffic requirements. In some cellular networks like WCDMA and LTE, coverage and capacity planning are linked and then mutually completed.

Finally, dimensioning of interfaces between different elements of the network is performed. This refers to transport dimensioning, and implies to identify the mean requirements for link capacities connecting the network elements. The two interfaces to be dimensioned in LTE are S1 and X2.

3. **Optimization**: the optimization process checks present network data accordance to the original plan during the implementation phase. This comparison ascertains any deviation in terms of coverage, capacity and quality, on both short and long terms. Current network data is obtained via extensive drive tests. If the network does not operate in its maximum efficiency, the results of field tests are injected into previous planning process in order to adjust what needs to be modified. Optimization process enables to identify then fix network problems. In LTE networks, the optimization process is assigned to the early phase of network planning, where the aim is to optimize performance by configuration changes (e.g. antenna tilts, heights adjustments, etc). Hence, this process allows the operator to use lower levels of infrastructure. This has a direct impact on decreasing required investments, and hence making tremendous cost savings.

Consequently, end users traffic features is a key factor in dimensioning future-planned cellular networks, especially the access segment. This work is positioned in the context of the LTE access dimensioning procedure. Indeed, we aim at analyzing end users devices impact on logical interfaces of access components, i.e. Small Cells. Next subsection describes our approach.

3.2.2 Proposed approach

As introduced in previous section, the required inputs for a LTE access network dimensioning are: traffic profile, radio network topology an radio interface performance values. Consequently, SCs backhaul network design is strongly related to access network needs in terms of required throughput. The traffic profile is the way user traffic is made up of data or/and signaling flows.

Yet the performed analysis is not sufficient to assess the capacity needs on different Small Cell connections. All the analyzed traffic represent load shares but don't show the impact of end users activity changes on targeted logical connections. For the reason, we propose to model then evaluate UE activity effect on traffic carried on SC interfaces. To accomplish this task, we focus our analysis on three key elements:

1. **SC logical interfaces**: Small Cells are the access nodes of the cellular network in the deployment use case we are targeting in this thesis. Hence they are the *intermediate* between subscribers devices and operator broadband delivery service. As a matter of fact, inputs/outputs traffic of SCs should be carefully studied. The traffic gates of a SC correspond to its logical interfaces. In our approach, we analyze a SC logical interfaces in order to determine quantitatively and qualitatively what kind of traffic it carries. This is performed in subsection 3.3.1.

2. **UE traffic**: subscribers devices are the key contributors in access traffic. As this traffic is highly diversified in terms of information in handles (applications traffic flows, signalization and management) and security requirements, the transport protocols accommodate this variety. On the other hand, some parts of an end user take different ways to be processed by the network elements, i.e. they travel through different SCs gates. UE traffic is analyzed by respect to those considerations in subsection 3.3.2.

3. **UE activity**: it denotes an UE behavior regarding exclusive data exchange in the network. This implies that an active UE sends/receives data to/from the network, while an idle one is only attached to one of the access network SCs. It is important to make this difference between UEs because the overall generated traffic changes depending on activity factor. This aspect is studied in section 3.4 through a time continuous Markov model.

The outputs of those three factors analyses allow to compute throughput on each SC logical interface.

3.3 Backhaul pipline traffic analysis

In LTE, new air interface and radio access called Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) were introduced in the 3GPP Releases 8 and 9. The new introduced interface is the X2 interface which establishes connections between eNodeB (or HeNodeB) to its neighboring eNodeBs (or HeNodeBs). It improves handover procedure reducing signaling messages and forwarding user traffic. The E-UTRAN (i.e. the LTE access network) is designed to provide enhanced user experience with full mobility by supporting high data rates and low latency. LTE has significantly improved the access air interface: this has yielded to higher throughput and radio interface capacity. As a consequence, LTE results on higher transport capacity demands in the access segment of the network. In full SCs based access networks, it is more critical to dimension the access network due to lower SCs capacities (compared to MCs) and tight economical constraints. Hence, it is crucial to plan properly the transport resources by taking into account growing traffic demand services diversity while investing in cost-efficient infrastructures.

3.3.1 Backhaul traffic: Small Cell perspective

The backhaul network provides interconnection between the access network, made up of SCs, and the core network. Taking into account that the elementary component of the access network is a SC, connecting the latter to the network means to consider all its logical connection with both service network and neighboring access nodes (i.e. Small Cells). In order to dimension appropriately the SCs backhaul, the access network should be analyzed in order to identify the vital requirements for the transport segment planning. The logical interfaces of the access nodes are examined. Figure 3.1 shows the logical architecture of a LE network based on Small Cells in the access part. A LTE Small cell has three logical interfaces:

- *S1 Interface*: the S1 interface connects the SC to the core network. It is made up of two interfaces:
  - The S1-MME : it connects the SC to MME nodes. This interface carries the control plane signaling messages between the SC and the core network. It supports signaling traffic like mobility management, access nodes configurations, inter-SC communication in case no direct connection between them, etc.

  ◦ The S1-U: it connects the SC to S-GW nodes. S1-U carries the user plane data between SC and the core network. It ensures the exchange of user plane data packets and is hence characterized as the user plane communication interface.

- *X2 Interface*: it interconnects a SC and its neighboring SCs nodes. The X2 interface ensures two main functions: 1) user mobility: it includes signaling messages exchange for handover preparation and execution packet forwarding for handover finalization, and 2) inter-eNodeB cooperation: it includes status and optimization procedures related information, such as intercell interference coordination (ICIC) and load control.

- *OAM Interface*: it connects the SC to the OAM System. Its main purpose is for the configuration of the Small Cell. It supports management plane messages such as configuration/self-configuration management, performance management and fault management.

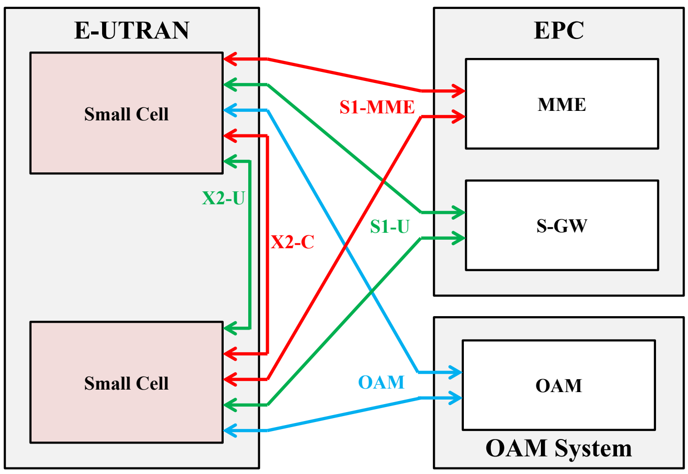


Figure 3.1: The logical architecture of the LTE access network

3.3.2 Backhaul traffic: End user perspective

As the backhaul pipline aggregate end users traffic flows, backhaul traffic might be divided up to following components [60]-[56] while considering a single (or average)

UE traffic:

- *S1 User Plane traffic*: it represents the biggest proportion of the overall traffic and it depends largely on the number of users sharing the SC's resource. The SC throughput can be then specified for two different loading conditions: busy times and quiet times. An estimation from network recorded statistics permits to get average generated traffic per user, for both uplink/downlink and busy/quiet hours. It is necessary to take into account the estimated traffic increase generated by different types of applications (VoIP, FTP, Web browsing,etc). This traffic is split into three sub-components:

  - User data: it refers to users payloads traffic, estimated without consideration of any protocol overhead. it represents the major part of backhaul traffic.

  - Transport Overhead: it depicts total transport protocol headers for GTP-U, UDP, IP and Ethernet protocols and radio overheads. Specifically, in order to enable the UE to keep the same IP address as its traffic moves between access and core nodes, this traffic is carried in "tunnels". GPRS Tunnelling Protocol (GTP) tunnels are used in LTE, UMTS and GSM cores. There is also Mobile IP protocol that can be used for tunneling traffic. Generally, the tunnel overhead proportion depends on the end user's packet size distribution. Larger packets (like video) incur smaller overheads whereas smaller packets (e.g. VoIP) have larger overheads. Herein we assume a transport overhead of 10% to represent the most general cases [60].

  - IPSec Overhead: IPSec protocol may be used by the operator to secure user plane data on the S1-U interface between the Small Cell and Serving Gateway, especially when the operator does not own the transport network. In this case, the IPSec Encapsulated Security Payload (ESP) in tunnel mode is used, which adds further overhead to the user data. We assume the IPSec EPS overhead is about 15% [60] in addition to transport overhead; which increases S1-U user plane overheads to 25% of this traffic.

- *X2 User Plane*: the user traffic carried out by X2 interface is predominated by forwarded user traffic during handovers. It means that in high mobility scenario, this traffic component has larger share: it can reach up to 10% of end user traffic. As we target normal mobility situation, we assume X2 user data is 4% of total user plane traffic. It is also impacted by the same transport and

IPSec overheads as for S1 user plane traffic.

- *S1 Control Plane*: it corresponds to signaling traffic between the Small Cell and core network; it may be estimated by 1% of user traffic. This traffic component incurs protocol (SCTP, UDP, IP and Ethernet) and IPsec (when used) overheads: it causes 179% and 95% control plane transport overhead with and without IPSec respectively.

- *X2 Control Plane*: it corresponds to signaling messages between Small Cells connected to each other via X2; it is evaluated by 1% of user traffic. The same transport and IPSec overheads proportions of S1 control plane are applicable.

- *OAM*: it reflects management messages exchanged with management system. It is represented as an additional 1 Mbps including transport overhead at the Small Cell. In our study, we neglect this component.

- *Synchronization signaling*: it depicts synchronization messages: it can be ignored and we assume it is negligible.

Figure 3.2 details the considered UE traffic components in our analysis with their ratios. Let OH_{CP} and OH_{UP} be the transport overheads share in control and user planes respectively. Table 3.1 gives the values of those ratios with/without IPSec.

The introduced backhaul traffic components shares should be derived from laboratory and field tests and/or already deployed networks with similar characteristics. The analysis should be done case-by-case since network topology impacts signaling load.

Let T_{UE} be the generated throughput by a single UE. In case we want to split signification of T_{UE} depending on different loading conditions, we consider:

- During busy hours, many end users devices are sharing the SC resource. It is less likely that all present active UEs on the SC have the same signal quality condition. T_{UE} indicates the average of busy hours traffic flows.

- During quiet times, there are fewer UEs (less than three) that would use the entire SC spectral resource. If the link is good enough, UEs can reach high data rates. T_{UE} denotes then the peak of quit times.

To sum up with UE traffic analysis, an UE generates signaling traffic on S1 (i.e. $T_{UE_{S1-C}}$) and on X2 (i.e. $T_{UE_{X2-C}}$); it generates data traffic on S1 ($T_{UE_{S1-U}}$) and on X2 ($T_{UE_{X2-U}}$). The overall generated flow by an UE is expressed in (3.1). s_{1_C},

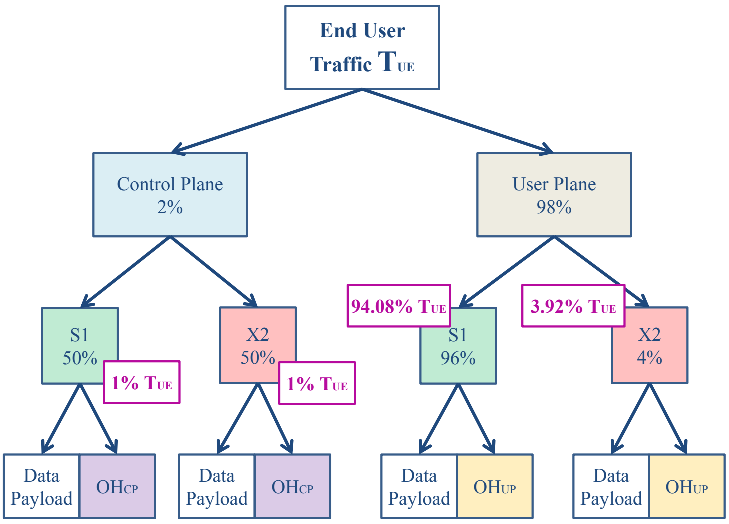


Figure 3.2: UE Traffic components

Table 3.1: Transport Overhead ratio for Control and User planes

	Without IPSec	With IPSec
Control Plane Overhead OH_{CP}	95%	179%
User Plane Overhead OH_{UP}	10%	25%

$x2_C$, $s1_U$ and $x2_U$ are proportions of $T_{UE_{S1-C}}$, $T_{UE_{X2-C}}$, $T_{UE_{S1-U}}$ and $T_{UE_{X2-U}}$ traffic flows by report to T_{UE} respectively.

$$\begin{cases} T_{UE} = T_{UE_{S1-C}} + T_{UE_{X2-C}} + T_{UE_{S1-U}} + T_{UE_{X2-U}} \\ s1_C = \dfrac{T_{UE_{S1-C}}}{T_{UE}} \\ x2_C = \dfrac{T_{UE_{X2-C}}}{T_{UE}} \\ s1_U = \dfrac{T_{UE_{S1-U}}}{T_{UE}} \\ x2_U = \dfrac{T_{UE_{X2-U}}}{T_{UE}} \\ s1_C + x2_C + s1_U + x2_U = 1 \end{cases} \tag{3.1}$$

Let $T_{UE_{S1-C-OH}}$, $T_{UE_{X2-C-OH}}$, $T_{UE_{S1-U-OH}}$ and $T_{UE_{X2-U-OH}}$ be the transport overheads ratios of control plane on S1, control plane on X2, user plane on S1 and user plane on X2 respectively. We define also $T_{UE_{S1-C-P}}$, $T_{UE_{X2-C-P}}$, $T_{UE_{S1-U-P}}$ and $T_{UE_{X2-U-P}}$ as payloads of control plane on S1, control plane on X2, user plane on S1 and user plane on X2 respectively. Hence, equations (3.2) and (3.3) detail the appropriate portions as a function of UE traffic T_{UE}.

$$\begin{cases} T_{UE_{S1-C-P}} = \dfrac{1}{(1+OH_{CP})} T_{UE_{S1-C}} = \dfrac{s1_C}{(1+OH_{CP})} T_{UE} \\ T_{UE_{X2-C-P}} = \dfrac{1}{(1+OH_{CP})} T_{UE_{X2-C}} = \dfrac{x2_C}{(1+OH_{CP})} T_{UE} \\ T_{UE_{S1-U-P}} = \dfrac{1}{(1+OH_{UP})} T_{UE_{S1-U}} = \dfrac{s1_U}{(1+OH_{UP})} T_{UE} \\ T_{UE_{X2-U-P}} = \dfrac{1}{(1+OH_{UP})} T_{UE_{X2-U}} = \dfrac{x2_U}{(1+OH_{UP})} T_{UE} \end{cases} \tag{3.2}$$

$$\begin{cases} T_{UE_{S1-C-OH}} = OH_{CP} \times T_{UE_{S1-C-P}} = \dfrac{s1_C \, OH_{CP}}{(1+OH_{CP})} T_{UE} \\ T_{UE_{X2-C-OH}} = OH_{CP} \times T_{UE_{X2-C-P}} = \dfrac{x2_C \, OH_{CP}}{(1+OH_{CP})} T_{UE} \\ T_{UE_{S1-U-OH}} = OH_{UP} \times T_{UE_{S1-U-P}} = \dfrac{s1_U \, OH_{UP}}{(1+OH_{UP})} T_{UE} \\ T_{UE_{X2-U-OH}} = OH_{UP} \times T_{UE_{X2-U-P}} = \dfrac{x2_U \, OH_{UP}}{(1+OH_{UP})} T_{UE} \end{cases} \tag{3.3}$$

Average UE throughput may be based on theoritical analysis/specifications (such as 3GPP UE categories specifications), on simulated networks or retrieved data from real networks probes. Theoritical end users throughput might be deducted from 3GPP theoretical specifications [8] which take into account different system bandwidths, MIMO configurations, and UE categories. Studies based on real networks tests (A study about the four French Mobile Operators [27]) can also be used to get UE traffic inputs.

3.4 Model description

3.4.1 Bi-dimensional Markov Chain

We consider an access cellular network with maximum N UEs devices. The UEs are attached to a SC node. This SC belongs to an access cellular network made up of many SCs. All SCs nodes are aggregated to the operator core network by a gateway (aGW). SCs communicate with each other via X2 interface and with aGW via S1 interface. In this model, one SC behavior towards generated traffics flows on S1 and X2 interfaces is analyzed. At this stage, we assume that the number of attached UEs to the considered SC is fixed over time.

Let $a(t)$ be the stochastic process representing the number of active UEs for a given cell station. Let $b(t)$ be the stochastic process representing the number of non-active UEs for the same cell station. The number of attached UEs to the SC is upper-bounded by the SC capacity N; i.e. at a time t, if $a(t) = i$ and $b(t) = j$, then $i + j \leq N$. Let T be the time scale.

Let S be the state space of the studied Markov model. The state space of the bi-dimensional process is the set of all possible values that the random couple of variables $\{a(t), b(t)\}$ can assume. This means:

$$\begin{gathered} \forall i \in (0, N), \forall j \in (0, N) \text{ such as } i + j \leq N \text{ then:} \\ \exists s_m \in S \text{ such as: } (i, j) \Leftrightarrow s_m \end{gathered} \tag{3.4}$$

$\{a(t), b(t)\}$ is a Markov process. Actually, $\{a(t), b(t)\}$ has the Markov or memoryless property: considering a certain value $\{a(t_1), b(t_1)\}$ at an instant t_1, the value of the bi-dimensional process $\{a(t_2), b(t_2)\}$ in the future at an instant t_2 such as $t_1 \leq t_2$ does not depend on its past value $\{a(t_0), b(t_0)\}$ such as $t_0 \leq t_1$; i.e. for $t_0 \leq t_1 \leq ... \leq t_n \leq t_{n+1}$,

$Pr(\{a(t_{n+1}), b(t_{n+1})\} = \{a_{n+1}, b_{n+1}\} | \{a(t_n), b(t_n)\} = \{a_n, b_n\}, ..., \{a(t_1), b(t_1)\} = \{a_1, b_1\}) = Pr(\{a(t_{n+1}), b(t_{n+1})\} = \{a_{n+1}, b_{n+1}\} | \{a(t_n), b(t_n)\} = \{a_n, b_n\})$

$\{a(t), b(t)\}$ is irreducible since all states in S can be reached from all other states, by following the transitions of the process.

$\{a(t), b(t)\}$ is stationary. For any $t_1, ..., t_n \in T$ and $t_1 + \tau, ..., t_n + \tau \in T (n \geq 1)$, the process's joint distributions are unaffected by the change in the time axis:

$F_{\{a(t_1+\tau), b(t_1+\tau)\} ... \{a(t_n+\tau), b(t_n+\tau)\}} = F_{\{a(t_1), b(t_1)\} ... \{a(t_n), b(t_n)\}}$

$\{a(t), b(t)\}$ is homogeneous as the behavior of the system does not depend on when it is observed. This means that the transition rates between states are independent of the time at which the transitions occur; i.e. for all t_0 and t_1, $Pr(\{a(t_0+\tau), b(t_0+\tau)\} = \{a_s, b_s\}) = Pr(\{a(t_1 + \tau), b(t_1 + \tau)\} = \{a_s, b_s\})$

We assume that each UE arrives at the cell at a rate λ and is served at a service rate μ. It might stay on the cell for σ seconds. p is the probability that the arriving UE is active. We assume that λ, μ, σ and p are constant and identical for all base stations.

The bi-dimensional process $\{a(t), b(t)\}$ is depicted in Figure 3.3 as a continuous-time Markov chain (CTMC).

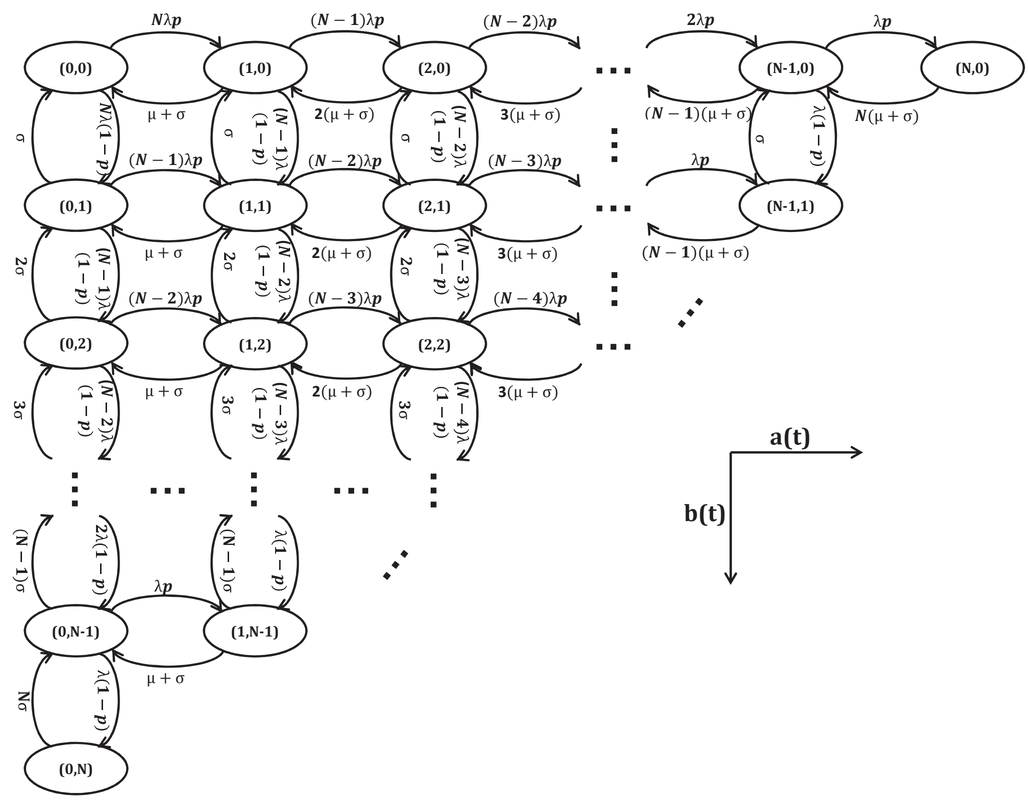


Figure 3.3: Bi-dimensional Markov chain diagram

The transition rate from state (i_0, j_0) to state (i_1, j_1) where $i_0, i_1, j_0, j_1 \in (0, N)$ is expressed using simplified notation: $P\{(i_1, j_1)|(i_0, j_0)\} = P\{(a(t) = i_1, b(t) = j_1)|(a(t) = i_0, b(t) = j_0)\}$

For this CTMC, the non-null one step transition rates are expressed as follows:

$$\text{For } i \in (0, N), \quad j \in (0, N), \quad i + j \leq N: \\ \begin{cases} P\{(i+1, j)|(i, j)\} = \lambda(N - i - j)p \\ P\{(i, j)|(i+1, j)\} = (i+1)(\mu + \sigma) \\ P\{(i, j+1)|(i, j)\} = \lambda(N - i - j)(1 - p) \\ P\{(i, j)|(i, j+1)\} = (j+1)\sigma \end{cases} \tag{3.5}$$

The first equation of (3.5) depicts the arrival of an active UE to the cell. When the cell covers i active UEs and j non-active UEs, the arrival of an active UE moves the cell state to $(i + 1, j)$. Since there are $(N - i - j)$ possible arriving UEs to the SC, the corresponding transition rate is $\lambda(N - i - j)p$. The second equation of (3.5) represents the departure of an active UE from the cell. Experiencing a departure of an active UE, the SC has i active UEs to serve and j non-active UEs that would stay in the cell for σ; The equivalent transition rate is $(i + 1)(\mu + \sigma)$. The third equation of (3.5) refers to the case of new non-active UE arriving. A non-active UE arrives to the SC with a probability $1 - p$ at the same rate λ. The transition rate is then $\lambda(N - i - j)(1 - p)$ as there are $(N - i - j)$ possible arrivals. The fourth equation of (3.5) accounts for the non-active UE leaving; a non-active UE stays for a certain duration in the SC before moving to another one. The departure of a non-active UE leads to a system moving to state (i, j) with rate $(j + 1)\sigma$.

Let Q be the infinitesimal generator matrix for the chain. This Markov process has $s = \frac{(N+1)(N+2)}{2}$ states. Q is a $s \times s$ matrix. Each entry at the mth row and nth column q_{mn} such as $s_m, s_n \in S$ and $m \neq n$ of the matrix corresponds to the instantaneous transition rate, i.e. transition rate from state m to state n. Diagonal entries are chosen to ensure null rows of Q, i.e.:

$$q_{mm} = - \sum_{s_n \in S, n \neq m} q_{mn} \tag{3.6}$$

A system performance analysis is usually focused on its behavior over wide time periods and especially in long term. We assume that in long term the system and the model reach *equilibrium* behavior, i.e. *state behavior*. Hence the model has regular and predictable behavior: the probability distribution of its random variable $\{a(t), b(t)\}$ over the state space S will not change. Then let $\pi_{i,j} = \lim_{t \to \infty} P\{a(t) = i, b(t) = j\}, i \in (0, N), j \in (0, N), i + j \leq N$ be the stationary probabilities distribution of the chain. This distribution exists since the bi-dimensional $\{a(t), b(t)\}$ is homogeneous, finite and irreducible Markov process.

To maintain the equilibrium in steady state of the system, we assume that the total probability flux out of a state is equal to the total probability flux into the state. For a state $s_m \in S$:

$$\pi_m \times \sum_{s_n \in S, n \neq m} q_{mn} = \sum_{s_n \in S, n \neq m} \pi_n \times q_{nm} \tag{3.7}$$

The combination of the global balance equations (3.6) and (3.7) leads to:

$$\sum_{s_m \in S} \pi_m \times q_{mn} = 0 \tag{3.8}$$

Let π be the row vector containing all model states $\pi_m, s_m \in S$. We can write the rearrangement of (3.8) as a matrix equation:

$$\pi Q = \mathbf{0} \tag{3.9}$$

The collection of s equations in (3.9) is irreducible. As $\{\pi_m\}$ is a probability distribution, the normalization condition of the chain is expressed:

$$\sum_{s_m \in S} \pi_m = 1 \tag{3.10}$$

Solving global balance and normalization condition equations (3.9) and (3.10) leads to determine vector π. It is mandatory to know probabilities π_m in order to derive performance measures since we are focusing on system performance analysis over extended time period. When equilibrium is reached, π_m is the probability to be in state s_m. By additionally deriving the amount of traffic flows generated by a each UE and transiting separately via S1 and X2 interfaces, generated traffic flows on the considered SC S1/X2 interfaces is obtained.

3.4.2 Average Throughput on interfaces S1 and X2

Let T_{S1} be the total throughput generated on S1 interface, and T_{X2} be the total generated throughput on X2 interface. Average values of those traffic flow are detailed in (3.11) and (3.12) respectively. As stated in (3.4), the equivalent stationary probability of state $s_m \in S$, noted π_m is $\pi_{i,j}$ such as $i \in (0, N)$ and $j \in (0, N)$. The latter expression is taken into consideration in the explanation of T_{S1} and T_{X2}.

$$\mathbb{E}[T_{S1}] = \sum_{j=0}^{N} \sum_{i=0}^{N-j} \pi_{i,j} [i\ (T_{UE_{S1-C}} + T_{UE_{S1-U}})] \tag{3.11}$$

$$\mathbb{E}[T_{X2}] = \sum_{j=0}^{N} \sum_{i=1}^{N-j} \pi_{i,j} [(i+j)\ T_{UE_{X2-C}} + i\ T_{UE_{X2-U}}] \tag{3.12}$$

The (3.9) and (3.10) equations system is solved using numerical methods on Maple to get the probabilities $\pi_{i,j}$ where $i \in (0, N)$ and $i \in (0, N)$. Throughputs (3.11) and (3.12) are presented and discussed in next section. We are also interested in cell blocking probability computed in equation (3.13). It is concluded from states where the cell reaches its capacity in terms of UEs:

$$P_B = \sum_{i=0}^{N} \pi_{i,N-i} \tag{3.13}$$

3.5 Evaluation

In this section, we discuss the SC logical interfaces performance regarding backhauling links capacities to carry end users traffic. We make separate analysis for S1 and X2 interfaces. The mean generated throughput generated in each one was expressed in previous section as a function of the average UE throughput fractions. Herein we present the most relevant numerical results for a set of default parameters (Table 3.2).

Table 3.2: Default parameters

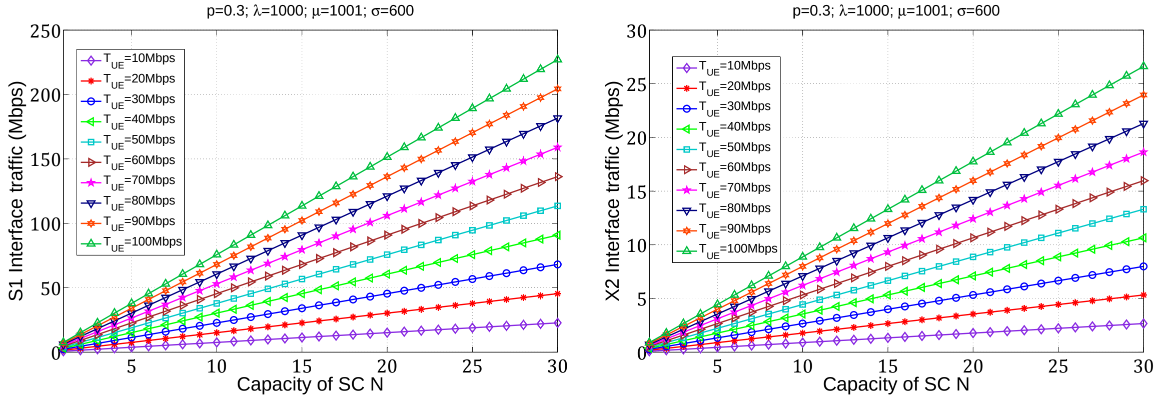
p	λ	μ	σ	T_{UE}
0.3	1000	1001	600	30Mbps

3.5.1 S1/X2 throughput

Figure 3.4 represents generated traffic flows on S1 (3.4a) and X2 (3.4b) interfaces for many SC capacity in terms of end users devices at low activity ($p = 0.3$). Both S1 and X2 traffic flows increase linearly as the number of arriving UEs increases; the increase of SC capacity leads to the increase of UEs population. It reflects the evident impact that has the more frequent new comers devices to the cell. Although active UEs are fewer than inactive ones, generated traffic on S1 interface maintains a linear evolution depending on overall UEs number. Which means that non-data traffic flows don't impact data traffic flows. It is due to the low considered percentage of signaling messages and that T_{S1} is made up mostly of user plane traffic.

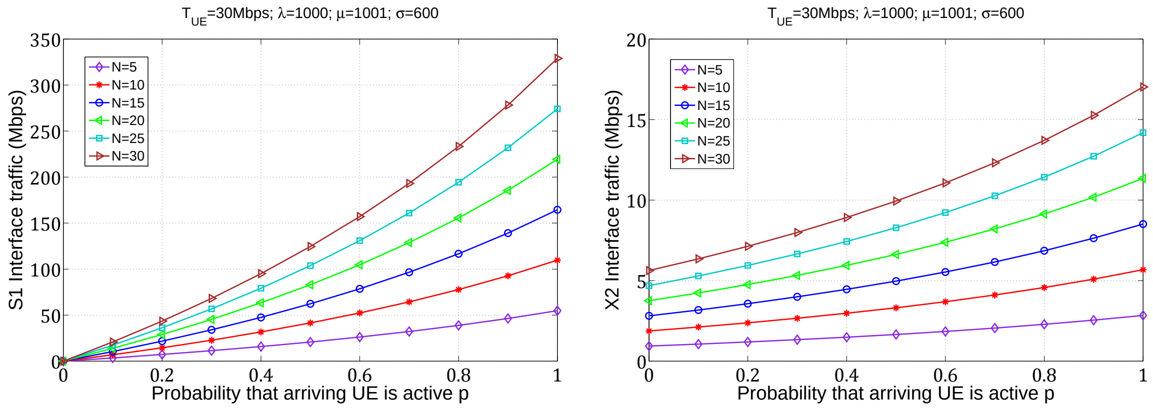
The two generated traffic flows become more consequent as the average end user throughput becomes greater. The considered range of UE traffic is chosen to represent both mean of busy hours and peak of quiet hours traffic flows (for both uplink and downlink): i) up to 10Mbps are to depict uplink mean of busy hours, ii) 10-30Mbps: downlink mean of busy hours, iii) 30-60Mbps: uplink peak of quiet hours and iv) more than 60Mbps: downlink peak of quiet hours. The variation of UEs throughput impacts directly the SC average spectral efficiency. During busy hours, the SC serves many UEs. Each UE has its own spectrum efficiency depending on the quality of its radio link. This infers that not all UEs will take advantage of available resource and transmit to their best efficiency; the SC spectral efficiency is consequently averaged by all its UEs spectrum efficiencies, and throughput. It is the busy times average throughput that is considered in backhauling provisioning planning. During quiet hours, there is at most one UE in the SC. As the SC throughput depends on its UE, there may be substantial variations depending whether the single UE gets good or bad radio links. Then if the UE has a good enough link, it gets the entire SC spectrum: this produces the *peak* throughput phenomenon. This throughput is also considered while planning backhaul provisioning. This yields to make a categorized analysis of UE throughput impact on logical interfaces traffic flows and hence helps making recommendations on wireless transport links depending on those sub-ranges frequency.

Figure 3.5 shows how generated flows on S1 (3.5a) and X2 (3.5b) interfaces evolve as a function of p, i.e. that the arriving UE is active. Both generated traffic flows on S1 and X2 increase linearly when p increases. When it is more probable that an UE is active, it is straightforward that the issued traffic is larger. However,



(a) S1 (b) X2

Figure 3.4: Generated traffic on logical interfaces versus N



(a) S1 (b) X2

Figure 3.5: Generated traffic on logical interfaces versus p

there is a difference between the increase of each interface traffic: T_{S1} augments rapidly according to p whereas T_{X2} progresses following a gentle gradient. Since p represents the probability of activity of an UE, it is obvious that only traffic depending on UE activity that will be dramatically impacted. T_{S1} is predominantly made up of user plane traffic then has big variances for p changes. Furthermore, data traffic implication on T_{X2} composition is very limited, then p has not that noticeable impact.

Figure 3.6 depicts generated traffic flows on interfaces S1 (3.6a) and X2 (3.6b) versus the average UE throughput at high activity ($p = 0.7$). As it might be noticed

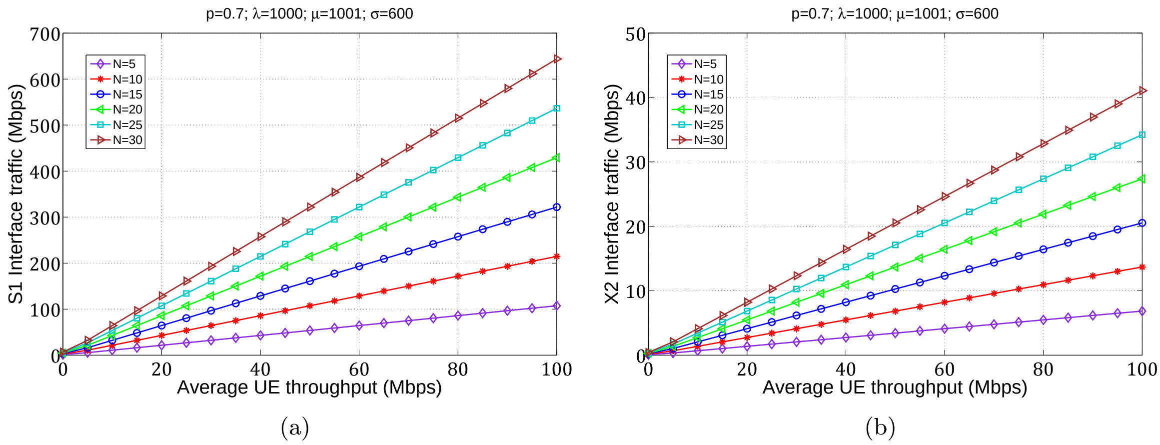


Figure 3.6: Generated traffic on logical interfaces versus T_{UE}

from Figure 3.4 and Figure 3.6, generated traffic on logical interfaces evolution is interchangeable between N and T_{UE}: discussion can be made as a function of N for many T_{UE} values, or vice versa, as a function of T_{UE} for many values of N. As the considered activity probability is quite high, generated traffic on S1 has more than doubled compared to the one noticed in lower activity (Figure 3.4a). However, X2 traffic is almost the same for both use cases of p. It confirms latter observations about Figure 3.5: UE activity has a very low impact on X2 throughput.

Figure 3.7 features generated traffic distribution between S1 and X2 interfaces for average end user throughput of 10Mbps (3.7a) and 50Mbps (3.7b). This corroborates that even for high demanding subscribers, the X2 traffic still represents a small part by report to overall traffic on logical interfaces. This would help recommending appropriated wireless links.

The noticed linearity in above presented results has an attractive advantage on future network planning. Actually this simple function facilitates the estimation of the generated throughput on both logical interfaces depending on number of subscribers devices, their activity and generated throughput by each one of them. It would suffice to determine the proportionality incline to predict traffic loads for many use cases of traffic profiles. Other input parameters would be easy to mix with the model for more accurate outputs.

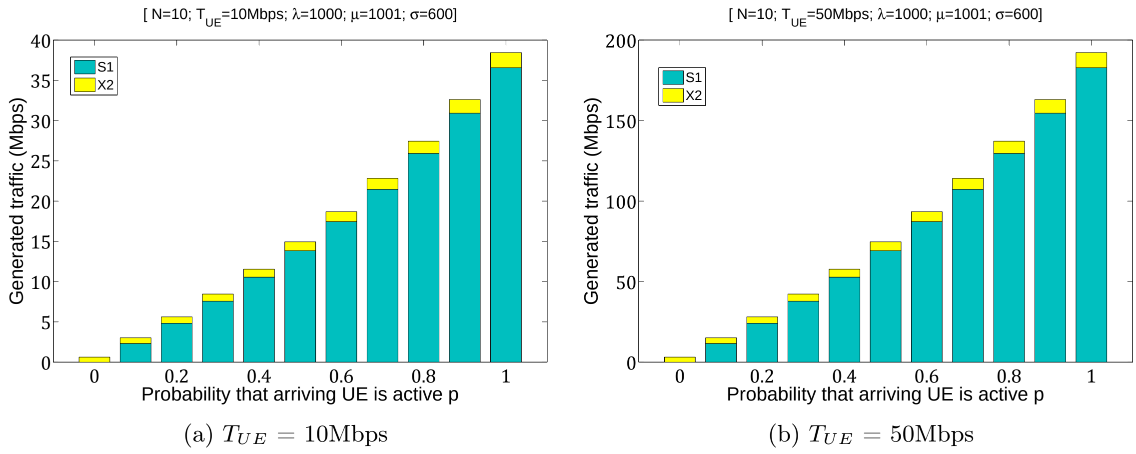


Figure 3.7: Generated traffic flows shares on interfaces S1 and X2 versus p

3.5.2 Blocking Probability

Figures 3.8 and 3.9 feature the blocking probability of the small cell as a function of UE activity probability p and average UE throughput T_{UE} respectively. Both figures point out that SC blocking probability decreases as SC capacity increases. Indeed, the more UEs the SC can serve, the less likely the SC reaches quickly its capacity limit and hence drops new UEs requests.

Figure 3.8 shows the blocking probability decreases as the UE activity probability increases: it even experiences a faster drop for higher SC capacities. This is an interesting result indicating that the activity behavior of new arriving UEs to the SC does not impact its capability of serving new UEs; it even enhances it. If we refer to Markov model states corresponding to full system, i.e.small cell, if the probability p is high it becomes less likely to move the system to full capacity state after the arriving of inactive UE: which corresponds to transition rate $\lambda(1-p)$. However, in case the move to full capacity system following an active UE arrival (i.e. transition rate: λp), it is more probable that the system processes the active UE and moves to precedent state, which is associated with higher probability $i(\mu+\sigma)$, $i \in (1, N)$.

Figure 3.9 shows how average UE throughput does not influence SC blocking probability. This is due to the fact that average UE throughput was not taken into account in the SC modeling and it was cou ted as an independent measure.

Those results permit to have a global idea about a SCN backhaul requirements

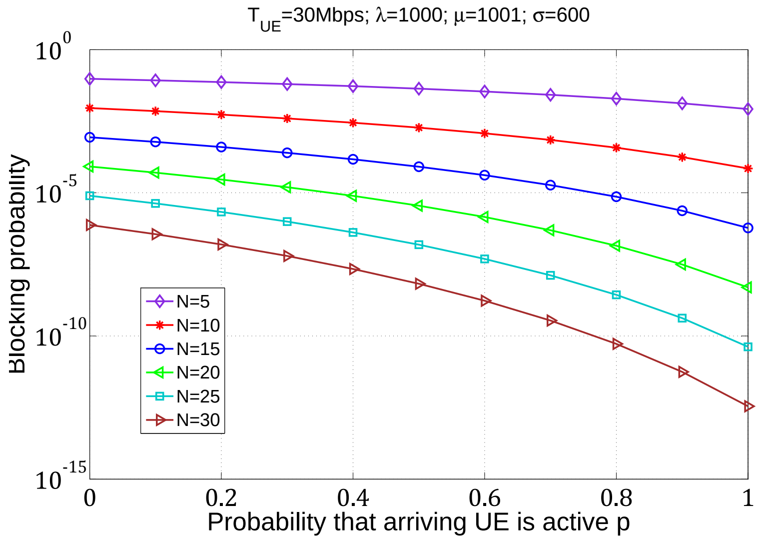


Figure 3.8: Blocking probability versus p

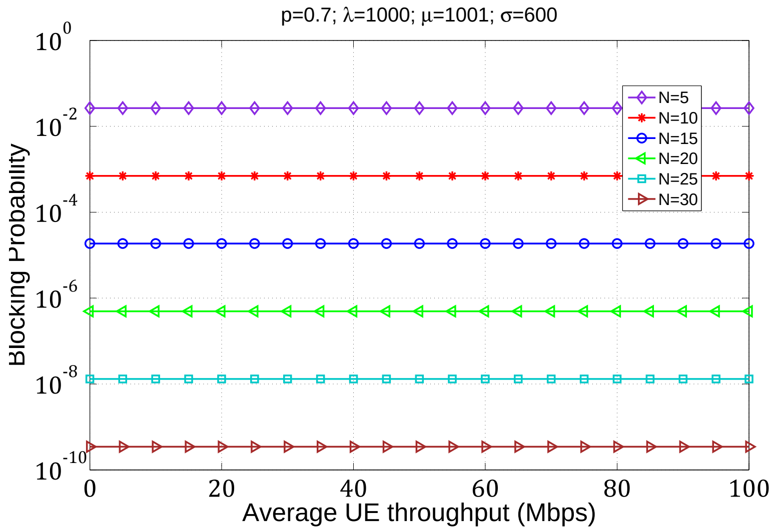
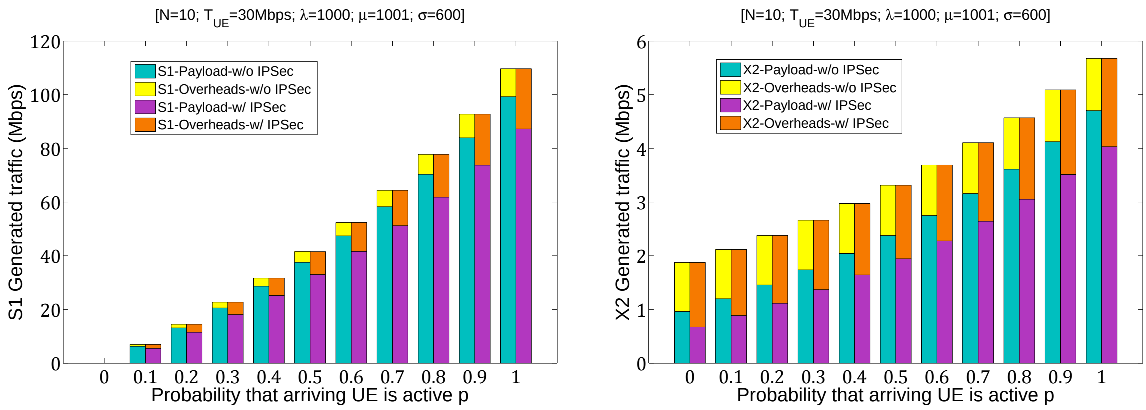


Figure 3.9: Blocking probability versus T_{UE}

regarding its links capacities: i) For aggregation links between the SC and aGW: high capacity links are needed to handle the important UEs throughputs. Those links should also have a good range if aGW is quiet far, or envisage relays, ii) For connecting links between access network SCs: medium capacity wireless links are largely sufficient to transport the low throughputs. Next step is to customize those recommendations for each area needs and their evolution over time. Hence, adjusted wireless backhaul technologies can be settled.

3.5.3 Overheads Consideration

Herein, we want to assess the composition of SC logical interfaces traffic regarding the implication of protocols overhead. Figures (3.10a) and (3.10b) depcit the ratios of protocols overhead (with and without IPSec) in S1 and X2 throughputs respectively. The impact of IPSec overhead is observed for both SC interfaces throughput: the overhead percentages are larger when packets are sent over secure tunnels. However, protocols overheads represent a significant part of X2 traffic: it may consume more than half carried load for the case of inactive arriving UEs. This shows the tremendous impact of protocol overhead on X2 control plane packets. As arriving UEs activity increases, the user plane carried by X2 is added to control plane traffic, and overhead impact is alleviated. Regarding S1 traffic, protocols overheads -even when using IPSec- share reasonable parts of the overall traffic; this is because S1 is predominated by user plane traffic that contains generally quiet long packets, overheads are less perceived in this case.



(a) S1 (b) X2

Figure 3.10: Overheads shares of Generated traffic flows on interfaces S1 and X2 versus p

3.6 Conclusion

In this chapter, we have analyzed the traffic carried by a SC backhaul segment. It was partitioned to ratios depending on their travel throughout different small cell logical interfaces, and whether they belong to user or control planes traffic flows. Then we have proposed a mathematical analysis of SC behavior towards activity of associated UEs throughput. It consisted on a Markov chain model that was solved to get stationary probabilities. Throughputs on interfaces (S1 and X2) of SC are derived as a function of average UE throughput. The latter was split into data and signalization flows. Numerical results showed how UE activity increase raised remarkably throughput on S1 interface of the access SC, but raised slowly X2 interface throughput. It is because an important part of UE data flow transits on S1 interface. Higher capacity links must be set on SC<−>aGW segment than on SC<−>SC segments. Shaping UEs traffic flows permits to adapt SC backhaul planning. This work contributes on choosing wise solutions regarding the wireless technologies to deploy for a SCN in green-fields.

In this chapter, we have focused our analysis on only one SC in the cellular system. In this context, the impact of UEs handovers to neighbors SCs is not considered dynamically, and attached users to each SC are changing over time; this impacts estimated flows traffic on SC logical interfaces.

Chapter 4

On enhancing Uplink Multi-Users MIMO transmissions

Contents

4.1 Introduction

As UL MU-MIMO transmissions are expected to be part of next 802.11ax [18]-[16], many research works in the literature tried to deal with UL MU-MIMO scheduling problem [41], [42], [47], [67], [70], [22]. Although those works proposed attractive UL-MU scheduling methods, their implementation is not straightforward. Actually, the main noticed limitation is the consideration of "a priori" resource allocation, stations selection and grouping, and transmission synchronization. Depending on whether the AP is involved in the UL MU transmission decision or not, or that (a)synchronized or (un)scheduled data transmissions are considered [46], those assumptions limit the implementation of those schemes in real Wi-Fi networks. HEW needs an UL MU mechanism that ensures a minimum backward compatibility and reduces changes to add in devices.

In this chapter, we propose novel mechanisms to enhance stations scheduling in UL MU-MIMO. A first mechanism, namely W2PAA, is proposed and then modeled and analyzed using a Semi-Markov chain. After that, an enhancement of WP2AA is provided, evaluated and compared to WP2AA through computer simulation. The main features of the second solution is that the scheduling stage duration is reduced by considering: 1) lower waiting time on the side of the AP when selecting new uplink simultaneous transmitters and 2) shortened backoff (BO) counters on stations sides by reducing contention windows. Both basic and enhanced versions of the scheme are implemented on custom simulator. A set of most relevant metrics is considered to analyze system performance using those schemes.

The remaining of this chapter is structured as follows. Section 4.2 describes the design of the proposed MAC scheduling protocols for UL MU-MIMO transmissions. A basic (W2PAA) and enhanced (W2PAA-E) versions are provided. Section 4.3 provides the semi-Markov model of W2PAA and evaluates its performance by computing aggregated throughput and average delay. Section 4.4 furnishes intensive simulations discussion by comparing SU-UL, W2PAA and W2PAA-E schemes. At the end, Section 4.5 sums up the chapter.

4.2 Design of the UL MU-MIMO scheduling scheme

4.2.1 Wait-to-Pick-As-Available: W2PAA

The UL-MU Transmission Opportunity (TXOP) starts by the transmission of the first RTS frame to the AP after the channel was sensed to be idle for DIFS duration. When the AP starts receiving this RTS frame from one of the N contending stations, it waits for limited time duration (dependent on the number of non-yet-allocated AP antennas) before replying with a CTS-equivalent frame to all stations. The AP associates to this waiting time a countdown timer T_w, which is computed and updated each time the AP receives a new RTS frame. T_w is computed as follows: the AP chooses a random integer n in the interval (1, $M - R_{RTSs}$), where R_{RTSs} is the number of currently received RTS frames; T_w is expressed as $n * (RTS + DIFS)$. If the AP receives a RTS frame before T_w elapses, T_w is recalculated and updated as stated above. If T_w elapses before receiving a new RTS or the AP reaches its MPR capability, the latter sends a grouped CTS (G-CTS) frame after SIFS: 1) to allowed stations, in order to inform them that they can transmit in the current UL-MU TXOP after a SIFS along with the allocated resources (called "winning stations"); 2) to remaining stations, to inform them about a differed contention on the channel (called "losing stations"). Losing stations assimilate this situation to a collision and double their backoff as stated on the standard. The scheduling stage is then accomplished (i.e. last countdown timer has expired or the MPR capacity of AP is reached) by sending the G-CTS frame. After SIFS duration, the simultaneous data transmission begins, wherein winning stations simultaneously transmit their UL data packets. Once data packets are successfully received, the AP acknowledges winning stations with a grouped ACK (G-ACK) frame after a SIFS. CTS and ACK frames are modified to include necessary information to inform all stations about the start of the simultaneous data transmission phase and allocated resources. The minimum time separating two RTS frames reception by the AP is DIFS. Although IEEE 802.11 standard does not specify packets timeouts, a timeout of SIFS+CTS+DIFS (time duration equivalent to EIFS [9]) is usually used for RTS frames. For herein proposed protocol, RTS messages timeout is extended to 'EIFS + (M-1)*(RTS + DIFS)'. Indeed, for each UL-MU TXOP, the maximum number of simultaneous transmission is M. Each station should consider the M-1 eventual winning stations and take into consideration their RTS frames transmissions over the channel in its own RTS frame transmission. Then each station should configure its timeout with legacy used value

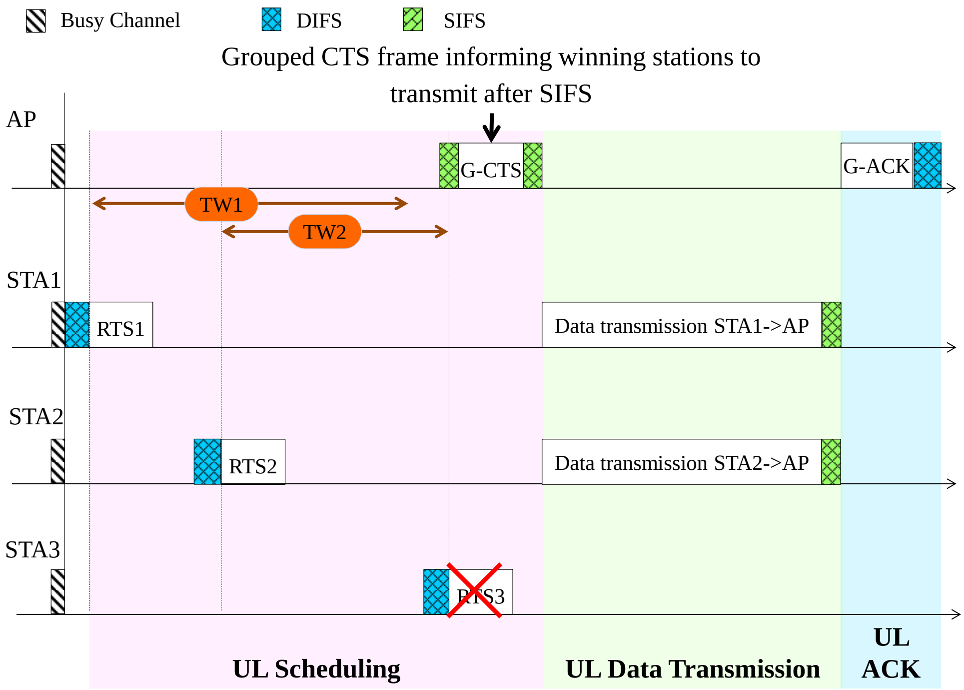


Figure 4.1: Example of WP2AA transmission protocol: two out of three contending single antenna stations win the UL MU TXOP to an AP with four antennas.

(i.e. EIFS) plus necessary duration time to transmit others (M-1) RTS frames. Figure 4.1 shows an example of an AP with four antennas and three contending stations. Only two stations win the UL-MU TXOP, since the timer expires before the AP receives the third RTS frame.

4.2.2 Enhanced W2PAA: W2PAA-E

In W2PAA, the AP waits for a random time duration when it receives a RTS frame before closing the UL-MU (TXOP). This random duration is calculated as the multiplication result between RTS+DIFS and a random integer chosen in the interval $(1, M - R_{RTSs})$, where M is the number of available antennas on the AP and R_{RTSs} is the updated number of received RTS frames. As we considered a serial contention mode, the AP can either choose one RTS frame or no RTS while down counting time. It would be enough to set the waiting time of the AP to an equivalent duration to necessary time to transmit a RTS frame from a station to the AP. However, the random waiting time adds unnecessary transmission delays. For this reason, we introduce two main changes to W2PAA and called the modified scheme protocol W2PAA Enhanced (W2PAA-E):

- The duration the AP waits before sending back a CTS equivalent frame is reduced to the average necessary duration to transmit an RTS frame. In UL-SU transmissions, a station launches its RTS frame BO counter after it starts sensing the channel idle for a DIFS period. In W2PAA-E transmissions, we note $CWmu_{min}$, c_{min}, $CWmu_{max}$ and c_{max} as the minimum contention windows; they correspond to backoff stage, the maximum contention windows and its corresponding BO stage respectively. This means that: $CWmu_{min} = 2^{c_{min}} - 1$ and $CWmu_{max} = 2^{c_{max}} - 1$. The BO slots number is randomly chosen between 0 and $CWmu_{min}$. After each packet collision, the minimum contention windows is doubled but cannot exceed $CWmu_{max}$,many consecutive collisions occur. Then, the necessary time associated with a RTS frame transmission is made up of three parts: 1) DIFS: the minimum duration that a station must sense the channel to be idle, 2) BO counter: after sensing the channel to be idle for DIFS, the station decreases its random BO counter and 3) RTS: the necessary time to send the RTS frame over the physical medium. In average, a given station packets would experience $c = \frac{c_{min}+c_{max}}{2}$ collisions. Consequently if $W = 2^c - 1$, the expected BO value is $\frac{2^c-1}{2}$ as detailed in (4.1):

$$\frac{1}{W+1}\sum_{i=0}^{W} i = \frac{W}{2} = \frac{2^c-1}{2} \tag{4.1}$$

  In this purpose, the new down count timer of the AP in W2PAA-E takes into consideration the three components of a RTS frame transmission duration. Indeed, the BO is replaced by its average value as shown in (4.2), where σ corresponds to system time slot.

$$RTS + DIFS + \frac{2^{\frac{c_{min}+c_{max}}{2}}-1}{2} \times \sigma \tag{4.2}$$

- The contention windows limits are reduced: both the minimum and maximum contention windows values are reduced in order to shorten the BO duration and hence reduce the time to send the RTS frame over the physical medium. This will also yield to reduce the waiting duration for the AP as the new duration time depends on those two parameters. W2PAA-E considers a minimum contention windows $CWmu_{min} = 1$ and a maximum contention window $CWmu_{max} = 31$.

Before comparing W2PAA and W2PAA-E performance, we first propose in next section an enhanced semi-Markov model of W2PAA taking into account backoff freezing.

4.3 Analytical Model of W2PAA

W2PAA was firstly evaluated in [33]. However, the performance evaluation procedure was based only on analytical model using a Semi-Markov model based on Bianchi model [24]. Although analytic results proved its effectiveness regarding system throughput and average delay, we propose here an enhanced semi-Markov model taking into account backoff freezing impact. The new model is derived from the enhanced Markov model studied in [68].

The main purposes of [68] model are: 1) explain backoff implication in channel occupancy time and 2) propose enhanced model taking into consideration this implication. [68]'s backoff analysis has led to two conclusions:

- Busy channel because of successful packet transmission: *A slot immediately following a successful transmission cannot be used for transmissions by any other STA, except the transmitting STA.*
- Busy channel because of collision: *The extra slot after the end of an EIFS* [1] *will not be used by any STA (either those involved in a collision or other STAs monitoring the channel).*

4.3.1 System Modeling

In order to evaluate the performance of W2PAA by report to the UL-SU transmission scheme, we analyze the system performance by using a Semi-Markov chain; this semi-Markov model is a modified version of [68]. We first examine the behavior of one station by using the semi-Markov model. This study yields to get the transmission probability that a station transmits a packet in a generic -randomly chosen- time slot. Second, we express system throughput and average delay for both SU and

[1] After a collision, a STA differs the transmission of concerned frame by interframe space EIFS.

W2PAA transmissions as a function of the obtained probability. It is worth nothing that we adopt all assumptions in [68], except the saturation conditions assumption. Indeed, in the proposed model we consider a Poisson arrival rate of data packets in each station, which introduces idle transition times between model states.

We consider a system composed of N contending stations for an UL -simultaneous or not- transmission with a single AP. Each station has a single antenna, while the AP has M antennas, i.e. the AP is capable of receiving up to M uplink streams from at maximum M selected stations. Let K be the maximum number of simultaneous uplink transmission during an UL-MU TXOP, i.e. K number of winning stations, $K = min(M, N)$. Each packet experiences a backoff time waiting period before being transmitted successfully or dropped after reaching the limit of allowed retransmissions.

Let $b(t)$ be the stochastic process representing the backoff time counter for a given station at time t and $s(t)$ the stochastic process representing the backoff stage of a given station at time t. This semi-Markov chain retakes [68] Markov chain and adds two extra states (Figure 4.2): the *Idle States* (I^-) and (I^+). The particularity of [68] is that stage 0 is differently modeled: the backoff counter states number is different whether the precedent state denotes a packet drop after maximum collisions (0^-) or a successful transmission (0^+). Our introduced *Idle States* correspond to states in which a STA waits for the generation of a new packet to transmit after: 1) a packet drop (due to maximum collisions): (I^-), and 2) a successful transmission: (I^+).

We assume that the packet arrival rate follows a Poisson distribution with an identical rate λ for all stations. Therefore, the mean holding time for each state $((I^-),(I^+))$, is $\frac{1}{\lambda}$. For states $(i, 0)$, $i \in [0, m]$, the holding time depends on collision and success packet duration, while for the remaining states we assume that the holding time is constant and equal to one time slot. We consider that the probability of collision p is constant and independent of the number of experienced retransmissions.

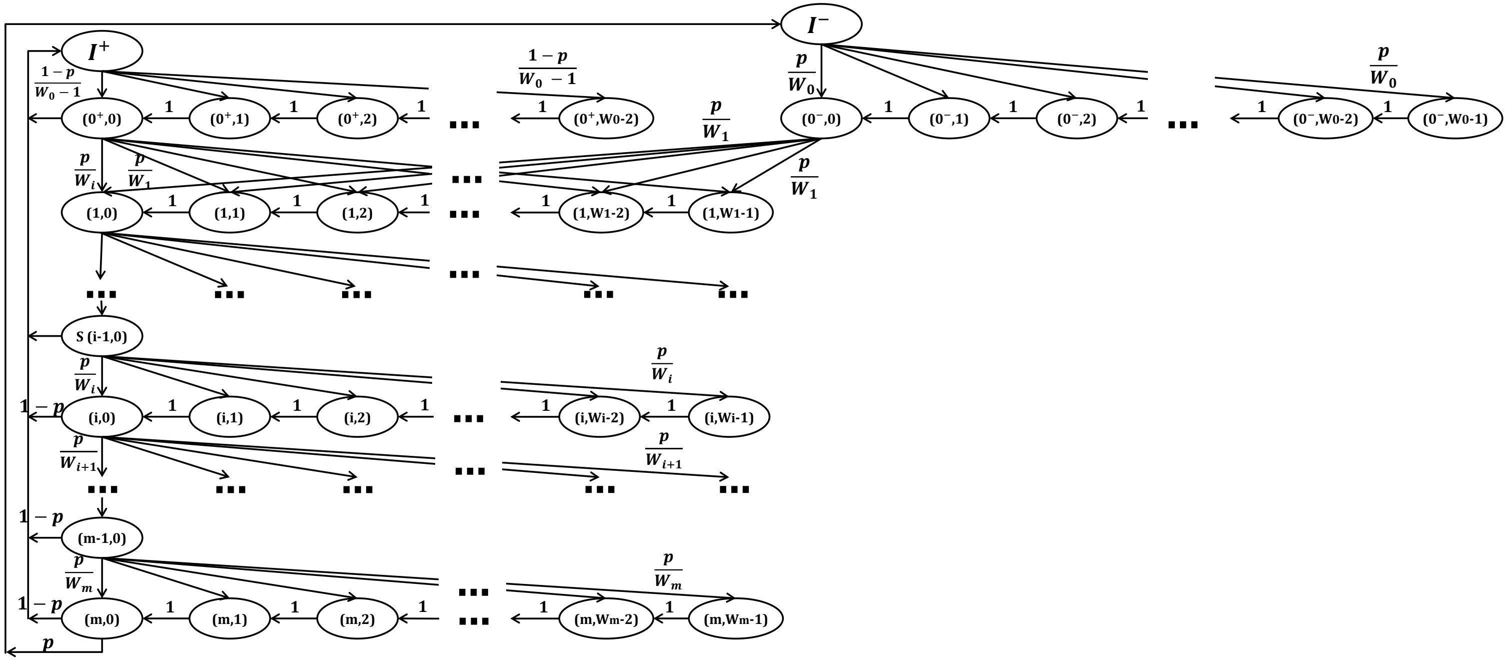


Figure 4.2: Semi-Markov Chain

Let τ be the probability that a station transmits in a randomly chosen time slot. τ is expressed as in equation (4.3):

$$\tau = \frac{\sum_{i=1}^{m} p^i + 1}{\frac{p^m}{\lambda} + \frac{1}{2}\sum_{i=1}^{m} p^i\left(2^i W + 1\right) + \frac{p^{m+2}+W}{2} + h\left(\sum_{i=1}^{m} p^i \ + 1\right)} \tag{4.3}$$

The collision probability p is expressed in equation (4.4):

$$p = 1 - (1-\tau)^{N-1} \tag{4.4}$$

The system of equations $\{(A.9), (4.4)\}$ is solved for SU-UL and W2PAA.

Let S_{su} and S_{mu} be the system throughput for SU and W2PAA respectively, it is the ratio of payload data bits transmitted and the duration of time spent to successfully transmit this payload. S_{su} and S_{mu} are expressed in (4.5) and (4.6):

$$S_{SU} = \frac{P_{tr}\, P_s^{SU}\, \overline{L}}{(1-P_{tr})\sigma + P_{tr} P_s^{SU} \overline{T_s^{SU}} + P_{tr}(1-P_s^{SU})\overline{T_c^{SU}}} \tag{4.5}$$

$$S_{MU} = \frac{\sum_{j=1}^{K} j\, P_{sj}\, P_{tr} \overline{L}}{(1-P_{tr})\sigma + \sum_{j=1}^{K} P_{tr} P_{sj} \overline{T_{sj}^{MU}} + P_{tr}(1-P_s^{MU})\overline{T_c^{MU}}} \tag{4.6}$$

Let D denotes the average delay. It is the average value of time interval from the instant a packet is at the Head of Line (HOL) of its MAC queue, ready to be transmitted, and the instant acknowledgment frame for this packet is received. It is expressed in equation (4.7):

$$D = \frac{\overline{L}N}{S} \times \left[1 - \frac{p^{m+1}\,\pi_{(0,0)}}{2}\left[\sum_{i=1}^{m}(W_i+1) \ + p^{m+1}(W+1) + Wp^m(1-p)\right]\right] \tag{4.7}$$

The Appendix A details the computing of all above mentioned measures.

4.3.2 Model discussion

Figures 4.3 and 4.4 show the analytic aggregated throughput and average delay as a function of contending stations. We observe from the throughput and delay plots that W2PAA protocol distinctly outperforms SU scheme, especially for big size networks. Further, the SU throughput is slightly decreasing as the network becomes larger.

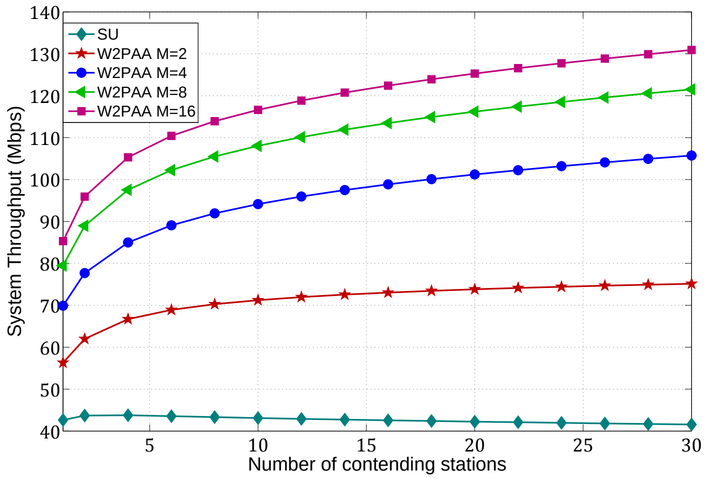


Figure 4.3: Analytic System Throughput versus number of contending stations

We argue this by the fact that higher number of contending stations implies higher contention rate, and then more frequent collisions in the channel, which causes this drop in system throughput. Also, this on-channel completion generates consequently longer waiting time for HOL packets (i.e. higher delays). Contrariwise, W2PAA throughput is increasing even if the number of contending stations increases and is enhanced for higher MPR capability. Average delay in W2PAA is greater for large network size, but is still better than SU. Actually, scheduling stage takes more time when there are many contention stations. Concerned packets wait more on their HOL.

Figure 4.5 depicts the probability of successful transmission for both UL-SU and W2PAA. We observe that W2PAA significantly enhances this probability, especially for high MPR capability values. Since each successful UL-MU transmission means many single packet transmissions, it allows carrying more data packet over the medium. We note that minimum of 90% of data packets are guaranteed to be successfully transmitted in large networks. There are more successful transmissions for higher AP MPR capability, which encourages investing in multiple antennas equipment as it reduces collisions and hence failed transmission. In the contrary, SU scheme decreases the number of successful transmissions in large networks. Indeed, collisions occur more often in highly populated network.

In next section, we compare performances of the basic and enhanced versions of W2PAA based on simulations on a custom made simulator.

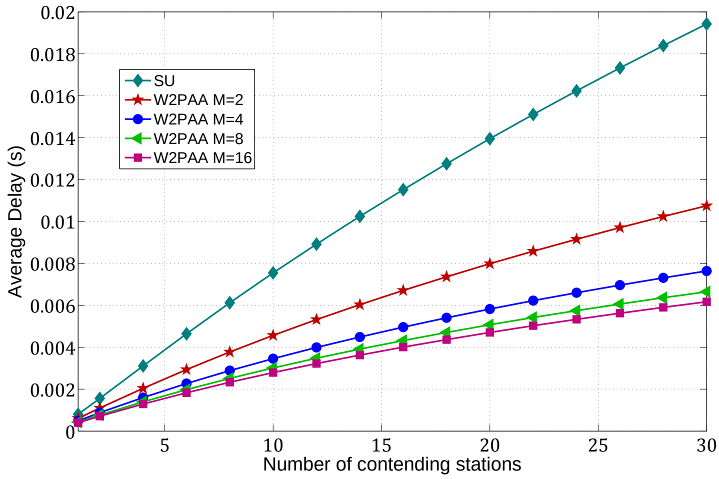


Figure 4.4: Analytic Average Delay versus number of contending stations

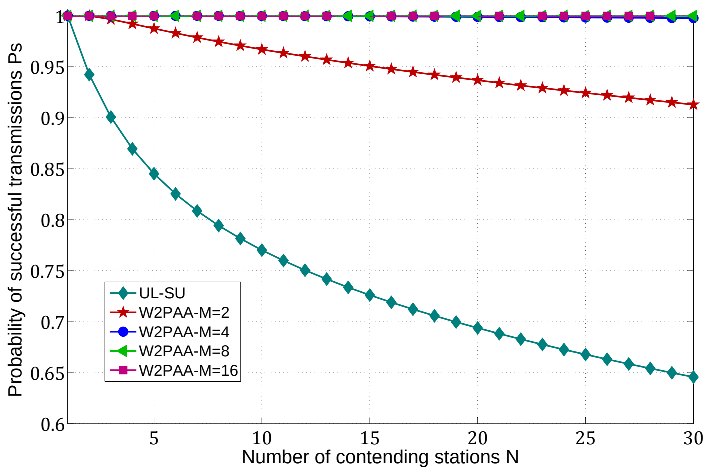


Figure 4.5: Probability of successful transmission versus number of contending stations

4.4 Simulated W2PAA and W2PAA-Enhanced

4.4.1 General Assumptions

In order to evaluate the performance of W2PAA-E and prove its efficiency over the W2PAA-E, a custom event-driven simulator is developed on Matlab. This simulator emulates mainly CSMA/CA method with virtual carrier sense and RTS/CTS exchange. Both W2PAA and W2PAA-E are implemented with MAC processing of the simulator and are enabled in simulation parameters configuration. A PHY-like processing is also supported by the simulator. The PHY layer consists on Signal-Noise-Ratio (SNR) based packet capture. The radio channel is modeled with lognormal shadowing propagation model; this permits to forecast the generated path loss in large scale fading environmements (both indoor and outdoor). This simulator is partially inspired from the one developped in [32].

In simulations, we consider one Basic Service Set (BSS) that consists of an AP and N user stations (STAs). The AP has M antennas: $M = 1$ in UL-SU simulations and $M \geq 2$ in UL-MU schemes. All stations have only one antenna. The stations are placed on a virtual circle around the AP. Stations are equally separated from their adjacent neighbors. Stations generate data packets and send them over MAC layer. All stations possess a Poisson traffic generator with rate λ.

Simulations parameters are chosen to best match the reference scenario depicting an outdoor large BSS and residential environemment (scenario 4a in [19]). This scenario take into account the presence of a building in the BSS.

All default simulations parameters are indicated in Table 4.1.

4.4.2 Performance evaluation metrics

To make this comparative performance analysis, we take into account certain performance metrics. Those metrics are chosen to meet Task Group ax (TGax) specifications [21]. Actually, the working group framed measure parameters that best reflect quality of user experience and system performance [20]. Most of below listed metrics are suggested by TGax to evaluate proposed mechanisms/protocols and procedures to achieve HEW goals [17]. Hereby, we reiterate those metrics meanings and list them in different performance groups:

- *User experience*: To evaluate user experience performance, we focus on per station throughput and packet average delay; we consider:
  - Average Per-STA Throughput: it is measured at MAC layer in uplink; from the instant the STA receives a packet from upper layer until its transmission is acknowledged.
  - Average Delay: it is the average delay of all data packets from all stations in

the BSS. For each packet, it is measured from the instant it is at the Head of Line (HOL) of the MAC queue, ready to be transmitted, and the instant acknowledgment frame for this packet is received.

- *BSS Capacity*:
  - BSS Aggregated Throughput (i.e. System Throughput): it is measured in uplink for all non-AP stations associated with the AP; it corresponds to all uplink traffic flows aggregated from all BSS stations.
- *MAC efficiency*:
  - Average Transmission latency: for each data packet, transmission latency is measured from the time that MAC layer receives a packet till the time that PHY layer starts transmitting.
- *Reliability measurement*:
  - Robustness: System robustness can be measured by first transmission success, average number of re/transmissions or re-transmission ratio. Herein we consider the re-transmission ratio. Let $TX1_{success}$, RTX_{NB} and RTX_{Ratio} be the ratio of successful first transmissions, the average number of re-/transmissions and the re-transmissions ratio respectively. $TX1_{success}$ is the ratio of the number of successfully transmitted data packets in the first attempt to the total number of data packets. RTX_{NB} is the ratio of the number of transmissions and re-transmissions experienced by data packets to the number of those packets. RTX_{Ratio} is the ratio of re-transmitted data packets to the total number of data packets. Actually, it is sufficient to consider only one of three measures to analyze reliability since it is possible to derive two of three measures knowing the third one; herein the dependence equations:

$$TX1_{success} = 1 - RTX_{Ratio} \tag{4.8}$$

$$RTX_{NB} = 1 + RTX_{Ratio} \tag{4.9}$$

  - Outage rate: it is deducted as the percentage of STAs with the per-STA throughput less than a chosen threshold (2-5Mbps according to [13] and [15]). It depicts the percentage of users whose links are unable to achieve a throughput threshold. This throughput threshold reflects a normal minimum satisfactory rate that all STAs should achieve in efficient systems.

- *Fairness*: protocol fairness refers to its ability to provide a per-user throughput *equitably*. We measure protocol fairness using Jain's fairness index, which is presenting many advantageous such as: independence of scale or unit, the intuitive relationship with user perception and its applicability of any number of users.

  - Jain's fairness index [40]: it is computed for per-STAs throughput using Raj Jain's equation. If T_{sta_i} is the throughput of station i where $i \in \{1, N\}$, and R_{d_i} its transmission capacity, then the fairness index is:

$$\mathcal{F}(T_{sta_1}, T_{sta_2}, ...T_{sta_N}) = \frac{(\sum_{i=1}^{N} \frac{R_{d_i}}{T_{sta_i}})^2}{N * \sum_{i=1}^{N} (\frac{R_{d_i}}{T_{sta_i}})^2} \tag{4.10}$$

4.4.3 Simulations results discussions

4.4.3.1 Impact of Network size

figure 4.6 shows the evolution of average per-STA throughput as a function of contending stations number (N). The first observation for all UL transmissions schemes is that per-STA throughput is dropping exponentially as the network becomes wider, i.e. there are more active users stations. Actually, as more stations want to send their data, there is more contention on limited channel resources. Some stations win the opportunity to transmit on the available resources, while other stations wait for the wireless medium to be free in order to send their frames. This automatically increases transmission duration of data packets, and hence reduces station throughput as the latter is inversely proportional to this duration.

Secondly, it is noticeable that uplink transmissions using multi-users mode have better per-STA throughput values than for the single user mode. It corroborates the usefulness of UL-MU transmissions in general, and W2PAA/W2PAA-E particularly. Moreover, the enhanced version of W2PAA outperforms its basic definition when comparing per-STA throughput for the same available antennas on the AP. In fact, reducing the duration a RTS frame takes to reach the AP yields to reduce the transmission duration of data packets and then to increase the per-STA throughput. When a STA is engaged in UL-MU TXOP, its engaged data packet is impacted by the duration time the AP waits before recruiting arriving RTS frames; so reducing this duration helps enhancing station throughput. Additionally, reducing the contention windows size allows to reduce backoff duration and then reduce the necessary time to reach the receiver; which also impact positively station throughput.

The obtained gain by using W2PAA-E in term of per-STA throughput is represented in figure (4.7a). The gain curves for each M use case zooms in the higher performance rendered by W2PAA-E against W2PAA. W2PAA-E permit to get a 140%-enhanced per-STA throughput for $N = 2$ with 16-antennas AP; the minimum achieved gain is around 4% for a network with 30 nodes and 2-antennas AP.

Regarding the impact of AP antennas on station throughput, there are different findings depending on network size. For relatively small to medium networks (up to 10 stations), available AP antennas have irregular impact on per-STA throughput for W2PAA. An antenna configuration for certain number of present stations is not always the best for other scenarios, with more or less stations. For example, obtained per-STA throughput with 16-antennas AP is globally the less efficient in the considered segment of the plot. This means that number of AP antennas does not drive this performance metric for W2PAA. However, W2PAA-E yields, globally, to enhanced per user throughput; but if the BSS has more than 6 stations, the best is that the AP is equipped with 8 instead of 16 antennas. For medium to big size network, per user performance increases as AP resources increases; but there is still a changing throughput for M=8 and M=16 depending on present stations. However, when the network becomes wider, obtained throughput for the latter use cases converges to close values. Hence, to get the higher throughput, it is clear that the best global antennas configurations are M=8 or M=16. However, since more antennas implies higher AP equipment costs and higher PHY processing complexity, is would be recommended to invest in 8-antennas APs. This is confirmed in figure (4.7b) which represents UL-MU per user throughput gains over SU mode. This figure shows how the discussed configurations of AP design have very close gains compared to legacy transmission mode.

As TGax targets to improve per user throughput by a minimum multiplication factor of four, figure (4.7b) attests how this performance may be achieved. Actually, starting from a network size of 7 stations, the per-STA throughput is quadrupled (i.e. gain ratio = 3) with an AP using 8 antennas and W2PAA-E scheme. This improvement is increasing as the network becomes wider and is 10.5 times better thanks to W2PAA-E and M=16. Although both UL-MU schemes exploiting 2 antennas never reach

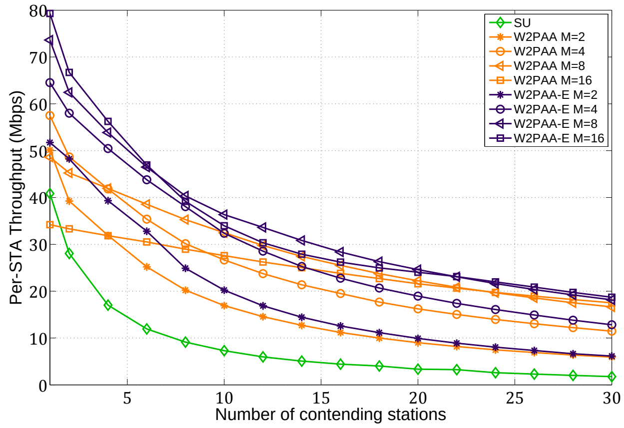
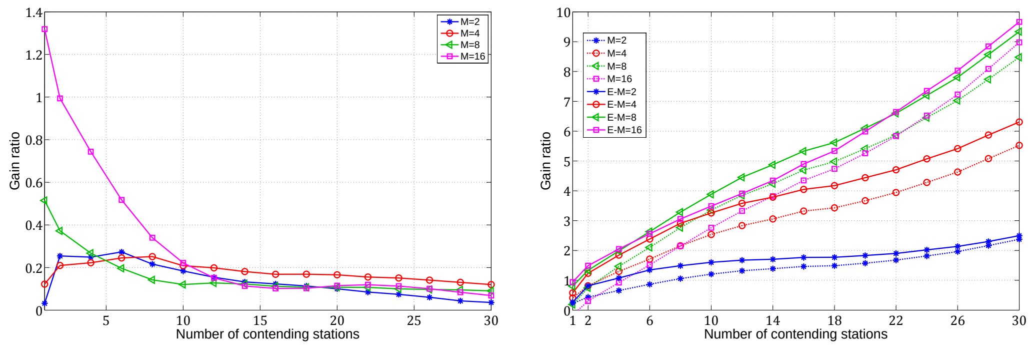


Figure 4.6: Per-STA Throughput as a function of number of contending stations

this gain target (at least for considered stations number and system parameters), W2PAA-E ranks first, especially with AP using greater number of antennas.



(a) W2PAA-E gain compared to W2PAA (b) UL-MU schemes gain compared to UL-SU

Figure 4.7: Per-STA Throughput gains

figure 4.8 represents the CDF of per-STA throughput, measured as a function of number of contending stations. Almost all curves have the form of the exponential distribution CDF. It is an interesting result since it becomes easier to predict per user behavior as the number of contending stations. Actually, per-STA throughput CDF may be approached by the known function: $x \to 1 - e^{-\beta x}$ where $\beta = \frac{1}{\mathbb{E}(T_{sta})}$; T_{sta} is the observed per user throughput vector.

Those throughput CDF functions permit to derive per-STA throughput measures at significant percentiles. Herein we consider three major percentiles:

- *5th percentile*: it measures the minimum throughput performance of stations at the cell edge. It is deducted as the corresponding per-STA throughput at 5% in the per user throughput CDF.

- *50th percentile* or *median*: it measures the average per user throughput of all stations in the considered BSS. It corresponds to the per-STA throughput at 50% of the CDF curve.

- *95th percentile*: it measures the maximum performance of stations at the cell center of the BSS. It is measured as the corresponding per user throughput to 95% in the CDF function.

Table 4.2 mentions considered percentiles measures for all UL transmission modes. To evaluate 5th percentile of per-STA throughput CDF, it is necessary to compare it to a threshold value fixed by the network operator and indicated by a set of technological parameters, such MCS indexes, channel bandwidth, etc. In this work, we refer to the SU mode as the threshold reference for MU transmissions. W2PAA-E allows enhanced minimal performance for cell edge stations, especially with higher number of streams. It means that at least 95% of BSS users gets better throughput. This fits IEEE working group requirements regarding this metric. The average performance requirement is also fitted since the median is three to seven times improved by adopting W2PAA-E protocol. This means that stations located at cell edge-AP midway have good throughput, with maximum performance for W2PAA-E using eight antennas. The TGax did not required an enhancement on 95th percentile but recommended to measure it in order to get an insight of top achievable performance. Again, an important enhancement is noticed with W2PAA-E and higher number of AP available resources. This measure indicates the per user throughput the cell center stations can reach.

figure 4.9 depicts packet average delay as a function of number of contending stations in the BSS. As noticed, the SU legacy scheme generates the highest delays for all network sizes. The more stations are contending to win the wireless medium, the larger is the delay experienced by a data packet. Since only one station is allowed to use the channel resource for certain time duration in the SU mode, increasing contending stations number decreases the chance to transmit on the channel; hence it postpones data packet transmission. However, UL-MU modes allows to many

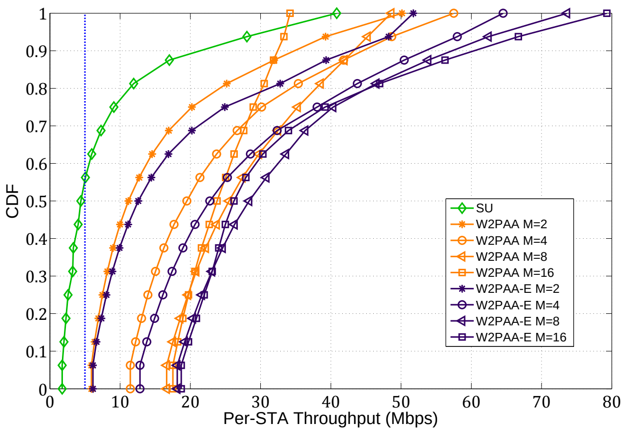


Figure 4.8: CDF of per-STA Throughput

contending stations to use the wireless medium simultaneously. Then many data packets are transmitted at the same time on different allocated resources in the same channel. This reduces considerably endured delay, especially in high contention environment.

It is also observable that the enhanced version of W2PAA outperforms its original version. The obtained gain of W2PAA-E compared to W2PAA is emphasized in figure 4.10. This figure points out a gain ranging from 3% to 56% and converging to about 10% for larger networks. The noticed improvement in average delay is due to the compression of UL-MU scheduling stage duration. Actually, n is the ratio of waiting duration to (RTS+DIFS) (refer to subsection 4.2.1). Each time it receives a RTS, the AP waits for a random $n \geq 1$ as introduced in W2PAA, while it waits only for $n = 1 + o(RTS + DIFS)$ in W2PAA-E. Another important finding regarding UL-MU transmissions is the produced average delay, which evolves linearly as a function of contending stations number; it facilitates the prediction of generated delays for other networks size by determining the slope of the line.

The average delay is even smaller for UL-MU transmissions using greater number of streams. Unlike per-STA throughput, average delay metric performance increases as the number of available antennas on the AP increases, i.e. M=16 permits the best delay reduction. It is recommended to invest in more antennas when targeting to reduce data delays.

figure 4.11 depicts the impact of number of contending stations on system through-

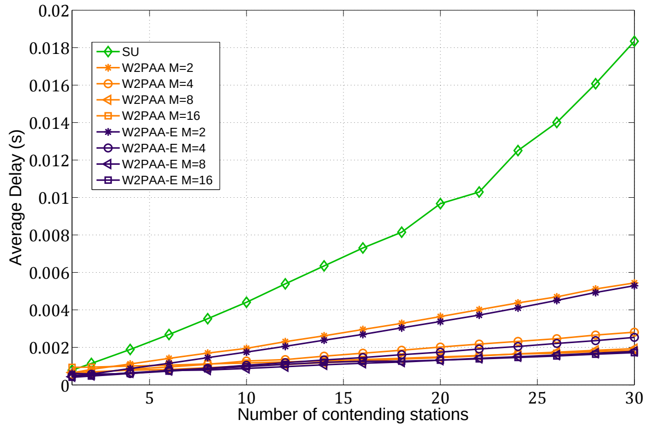


Figure 4.9: Average Delay as a function of number of contending stations

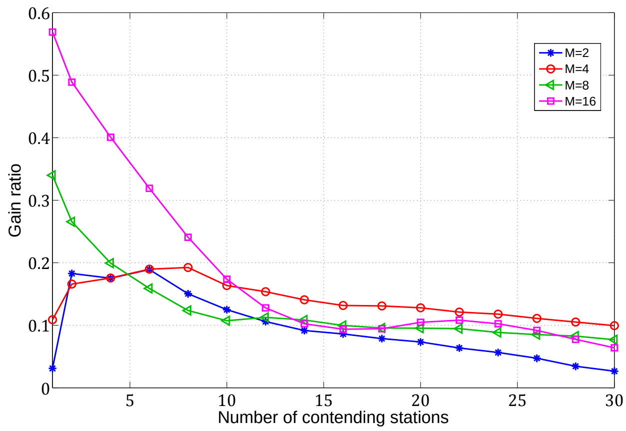


Figure 4.10: Average Delay gain

put, i.e. aggregated throughput of the BSS. It indicates the maximum throughput that it is possible to transmit in the full bandwidth. It is noticeable that UL-MU modes outshine the legacy SU. It supports findings about average per-STA throughput since the BSS throughput may be obtained by aggregating all BSS users throuputs. It also sustain the consequent improvement of W2PAA-E over W2PAA. For example, for a network made up of 12 stations, W2PAA-E allows enhanced BSS capacity by 175% compared to W2PAA and 25000% compared to SU scheme.

Additionally, UL-MU mode grants an increasing system throughput as the the AP exploits more antennas. This helps to make decision on deployed antennas on the

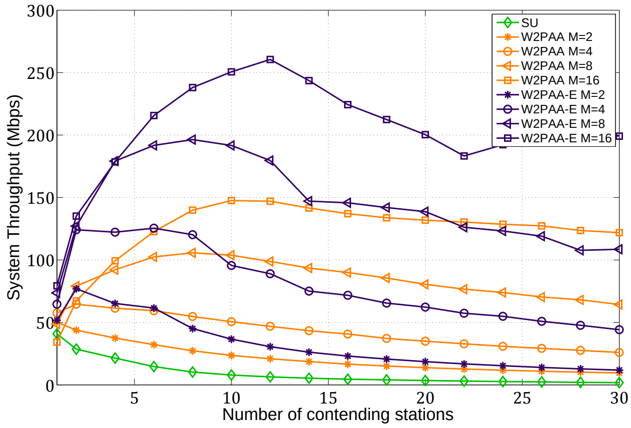


Figure 4.11: System Throughput as a function of number of contending stations

AP equipment depending on client/operator needs. However, unlike the SU and two antennas configurations of W2PPA (i.e. M=2 and M=4) whose throughput is decreasing as the network is larger, W2PAA-E ensures an increasing capacity up to certain network size threshold, and then starts to fall in. This provides an overview of network size limit above which users experience starts to drop. This network size threshold depends on the number of used spatial streams. Accordingly, the higher is the latter, the higher is the threshold. Moreover, this threshold is equal or less than used antennas for W2PAA-E: N=2 for M=2, N=4 for M=4 and N=12 for M=16. Hence it is easier to identify the limit above which system performance declines.

Fig .4.12 shows the transmission latency against the number of contending stations. As perceived, SU scheme generates higher medium acquisition delays, especially for large networks. The gap between UL SU and MU schemes is raising as the number of contending stations augment. Indeed, the transmission latency evaluates the introduced delay by MAC layer processing; this means that this delay contains the time duration consumed by BO procedure and handshaking RTS/CTS mechanism. Since the SU scheme allows only one station to access the medium, the packet spends longer time waiting in the MAC before it can be transferred to PHY processing. However, UL-MU scheme aggregates many RTS frames: instead of a packet waits for the channel to be free, its RTS frame is engaged in UL-MU TXOP, and stays less in the MAC layer. The MAC sojourn is even reduced with W2PAA-E thanks to: 1) reduction of the count-down timer duration and 2) shortening of BO timer (i.e. CW_{min} reduction). MAC efficiency is also enhanced for more available spacial

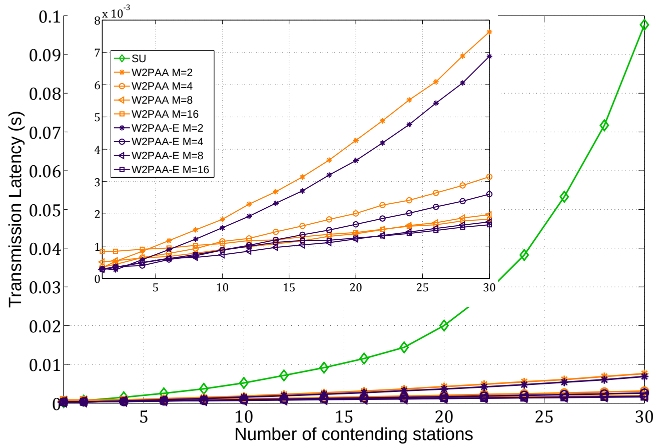


Figure 4.12: Transmission Latency as a function of number of contending stations

resources. The transmission latency does not exceed 7ms for a BSS with thirty stations and a two antennas AP performing W2PAA-E. This enables high efficiency use of MAC and reduces overall packet delay (as discussed above).

In our simulator, a packet is re-transmitted if its timeout expires before its acknowledgement frame is received. Fig . 4.13 represent the re-transmission ratio against the number of contending stations in the BSS. This figure points out how SU scheme allows the best performance with a null re-transmission rate, while W2PAA-E ranks second with a ratio between 0% and 2%; W2PAA generates a ratio up to 24%. In CSMA/CA, the station checks regularly if the medium is clear to send its frame. Using SU mode, the station keeps its frame until it senses the channel is idle for DIFS period. The station sends its frame over the medium normally, unless another station chooses the same BO duration (which is uncommon) a collision happens and each station differs the transmission of its packet. However, when using one of the introduced UL-MU schemes, the station may senses the medium idle for a DIFS period and sends its frame over the channel, while a count-down timer is launched on the AP, then there are two possibilities: 1) the frame arrives at the MAC layer of the AP before its count-down timer expires, so the frame is well transmitted and the AP continues its UL-MU scheduling procedure; and 2) the frame arrives after the AP count-down timer expires, so the frame is not considered by the AP since it has closed its UL-MU TXOP, i.e. the frame is lost and the AP continues its procedure.

The better performance is ensured with W2PAA-E compared to W2PAA. This is due to the reduction of BO timer introduced in W2PAA-E. Actually, the station

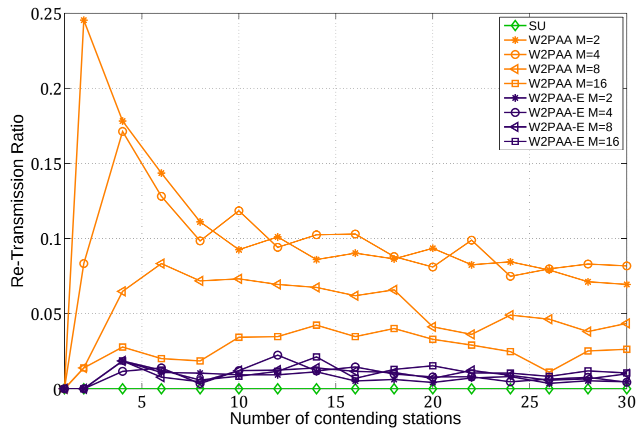


Figure 4.13: Re-Transmission Ratio vs. the number of contending stations

launches the BO procedures after its senses the medium idle for the DIFS period; so even if AP timer shortening suggests an increasing probability of non-recruiting frames, the shortening of frame transmission from the side of the station yields to reduce this probability.

As the AP timer duration no more depends on the number of its antennas in W2PAA-E, the re-transmission ratio is slightly oscillating around 1%; while it has wider fluctuations around the value 8% in W2PAA. In the latter scheme, the impact of AP antennas number on this metric is clear: the more antennas has the AP, the smaller is the re-transmission rate. Given that the UL-MU TXOP average duration depends on AP resources, the shorter is this duration, the more frequent are packets re-transmissions. Hence W2PAA-E operates in a more acceptable re-transmission rate than W2PAA, which makes it better solution when choosing between the two schemes.

As stated before, the outage rate indicates the percentage of clients with the per user throughput less than 5Mbps. In figure 4.8, the blue dashed line represents this throughput threshold and is drawn to show its eventual intersection with per-STA throughput CDFs of all UL transmissions schemes. As observed, this line crosses only CDF of SU mode, which means that more than half users can't reach this minimum requirement of throughput. It means also that UL-MU schemes achieve the metric requirement in this use case, supplementary metric measures are recommended for many system parameters.

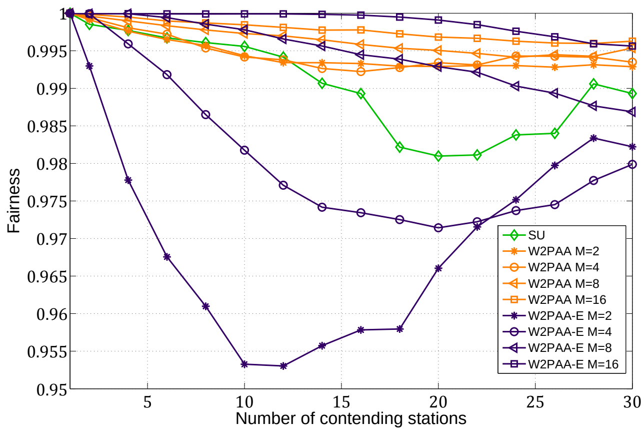


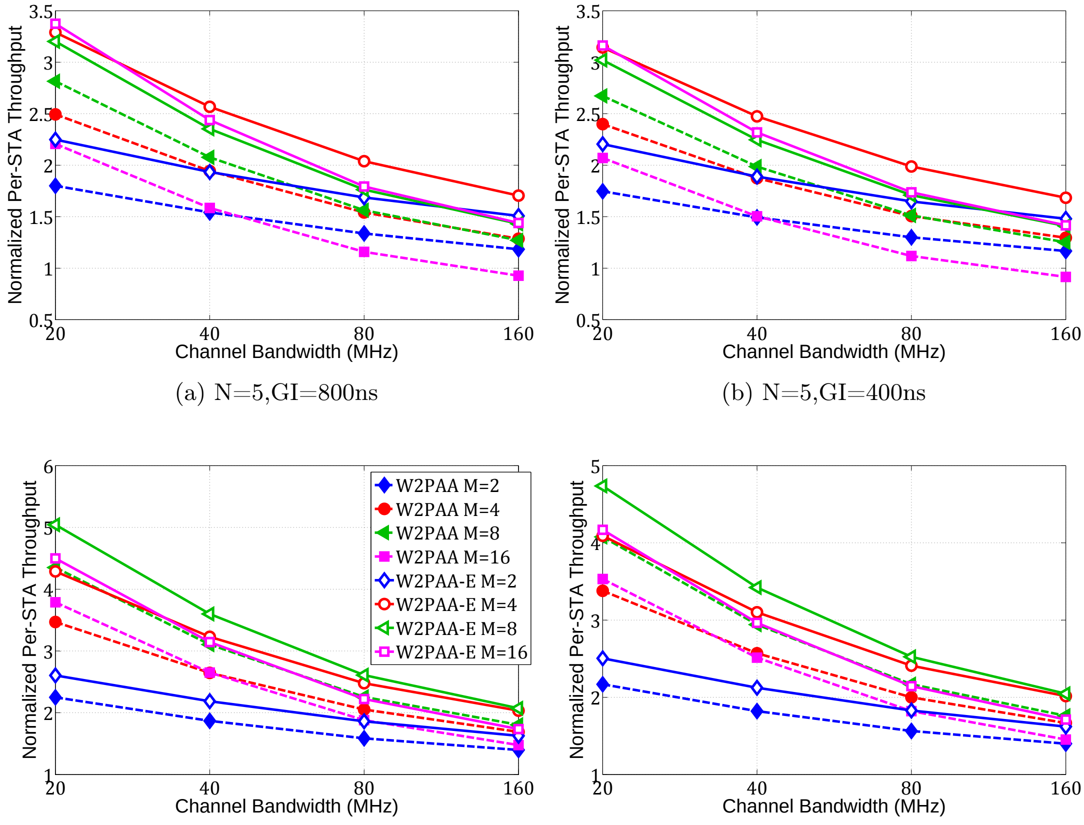
Figure 4.14: Fairness Index against number of contending stations

figure 4.14 features the impact of number of contending stations on system fairness. The higher the fairness index is, the higher the degree of fairness is. This measure decreases for all schemes as the number on users becomes high. It is W2PAA that offers the fairest share of throughput with an average value of about 99.5%. Baseline scheme yields to a fair allocation ranging from 98% (N=20) to 100% (N=1). However, W2PAA-E exhibits a changing fairness depending on the number of used antennas: M=16 permits the best fairness performance over all schemes while M=2 declines it.

Theoretically, the fairness index ranges from $\frac{1}{N}$ to 1. Consequently, for a network with at least two nodes, the fairness index scope is [50%, 100%]. Compared to obtained simulated fairness index, the latter is much more converging to a perfect fair allocation. Since the multi-rate transmission used in IEEE 802.11 is not considered in the simulator, and all stations send packets with the same length, the observed disparity is caused by small differences in packets transmission duration; in this case, W2PAA-E "unfairness" reflects more transmission duration "unfairness".

4.4.3.2 Impact of Channel bandwidth

figure 4.15 represents the normalized per-STA throughput as a function of channel bandwidth for two network sizes and when using different GI: 800us and 400us. The per-user throughput is decreasing as the channel is wider. Indeed, this is due to the fact that in large channels, legacy UL transmissions can reach higher data rates than



(a) N=5,GI=800ns (b) N=5,GI=400ns

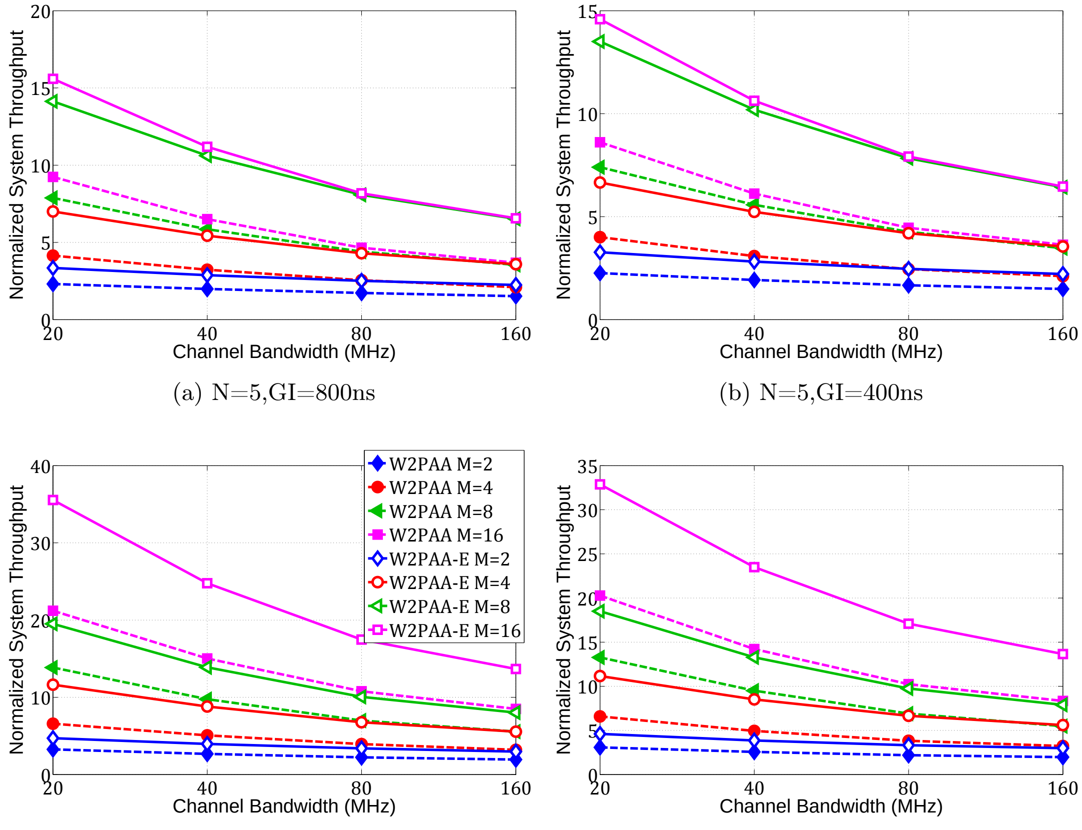
(c) N=10,GI=800ns (d) N=10,GI=400ns

Figure 4.15: Normalized Per-STA Throughput versus Channel Bandwidth

in standard channels; the impact of UL-MU schemes on perceived throughput by each client declines.

For the same case of AP antennas number, W2PAA-E outperforms W2PAA. However, the number of antennas that maximizes per-user throughput is different for the two size uses cases: $M = 4$ for $N = 5$ and $M = 8$ for $N = 10$ when using W2PAA-E. This implies that the optimum AP resources number that achieves stable high performance for different channel widths depends on network size. This optimum number may be deducted from the network size: it corresponds to closest value of antennas number to the considered network size.

figure 4.16 depicts the normalized system throughput versus channel width for two sizes networks. The normalized BSS throughput is also decreasing as the channel is wider. As wide channels permit higher data rates for SU communications, hence the



(a) N=5,GI=800ns

(b) N=5,GI=400ns

(c) N=10,GI=800ns

(d) N=10,GI=400ns

Figure 4.16: Normalized System Throughput versus Channel Bandwidth

brought enhancements by MU schemes are less significant.

In the contrary, the normalized BSS throughput is improved as the AP has more available resources for UL-MU transmissions for both considered network sizes.

figure 4.17 shows the average delay versus channel width for the above considered network sizes. The average delay is enhanced for wide channels. Actually, The use of wider channels leads to higher data transmission rates for the same MCS indexes. This means that both control and data frames are sent over the medium at higher speeds, which leads to reduce delays experienced by data packets.

As for the normalized per-STA throughput metric, the average delay has the same performance interpretation regarding UL-MU schemes impact, especially W2PAA-E improvements. In fact, the average delay is minimized for different AP antennas number for each network size.

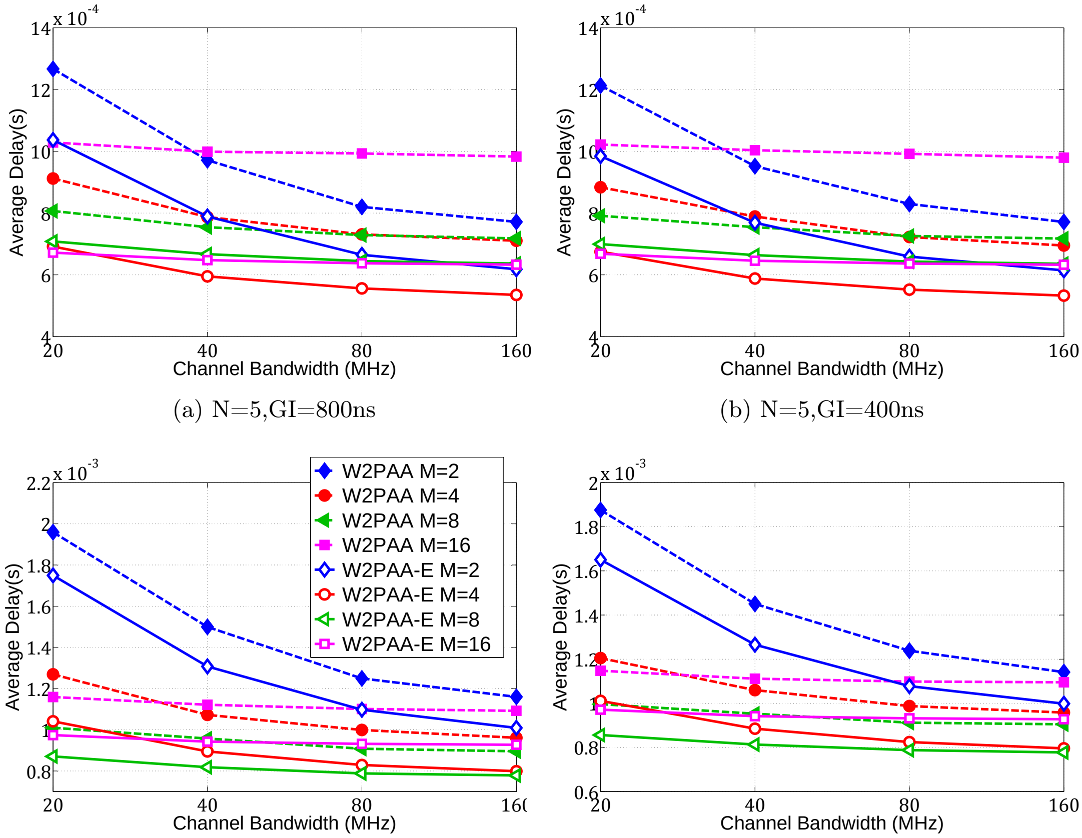
The guard interval (GI) is the period of time between transmitted OFDM symbols. The GI is introduced before each transmitted symbol to eliminate inter-symbol interference (ISI). Since in 802.11n, the default GI is 800ns and the optional one is 400ns. The latter, called short GI, should be used only in good RF conditions; otherwise ISI will corrupt data transmission, and hence reduce throughput. When observing the impact of GI length on discussed performance metrics regarding channel bandwidth, the short GI lowers slightly the normalized values of both per-STA and BSS throughput flows, whereas the average delay is enhanced. Since short GI reduces overheads, it helps reducing transmission delays, and should improve throughput. However, while becoming too short, the GI will foster ISI and then reducing throughput. A good compromise of long/short GI should be fulfilled to enhance overall performance.

4.4.3.3 Impact of Modulation and Coding Scheme

The Modulation and Coding Scheme (MCS) index refers to the combination of three elements: number of spatial streams, modulation type and coding rate. It indicates only the data rate of the wireless link, i.e. the over the air rate. The usable throughput is usually lower this data rate, unless perfect channel conditions. Each MCS index data rate depends on used channel bandwidth and GI length. A list of MCS indexes and their offered data rates for 802.11n and 802.11ac is detailed in [2]. Hereafter we analyze the impact of MCS indexes on most relevant performance metrics in the default channel bandwidth 20MHz.

figure 4.18 features the normalized per-STA throughput versus MCS indexes for two different network sizes. This normalized metric is decreasing as the MCS indexes are higher, i.e. as data rates are higher. When data frames are sent over the medium at high data rates, the SU mode throughput is increased and the UL schemes improvements are less noticeable.

W2PAA-E offers generally the best per-user enhancement, especially when the AP is equipped with many antennas. But in the $N = 10$ network, it is better to use eight antennas rather than sixteen when using MCS indexes greater than 3. This infers that the used number of AP resources should be adjusted depending on network size and configured data rates. When data rate adaptation is enabled, devices change dynamically the data rate in which they send their data packets in order to reach peak



(a) N=5,GI=800ns (b) N=5,GI=400ns

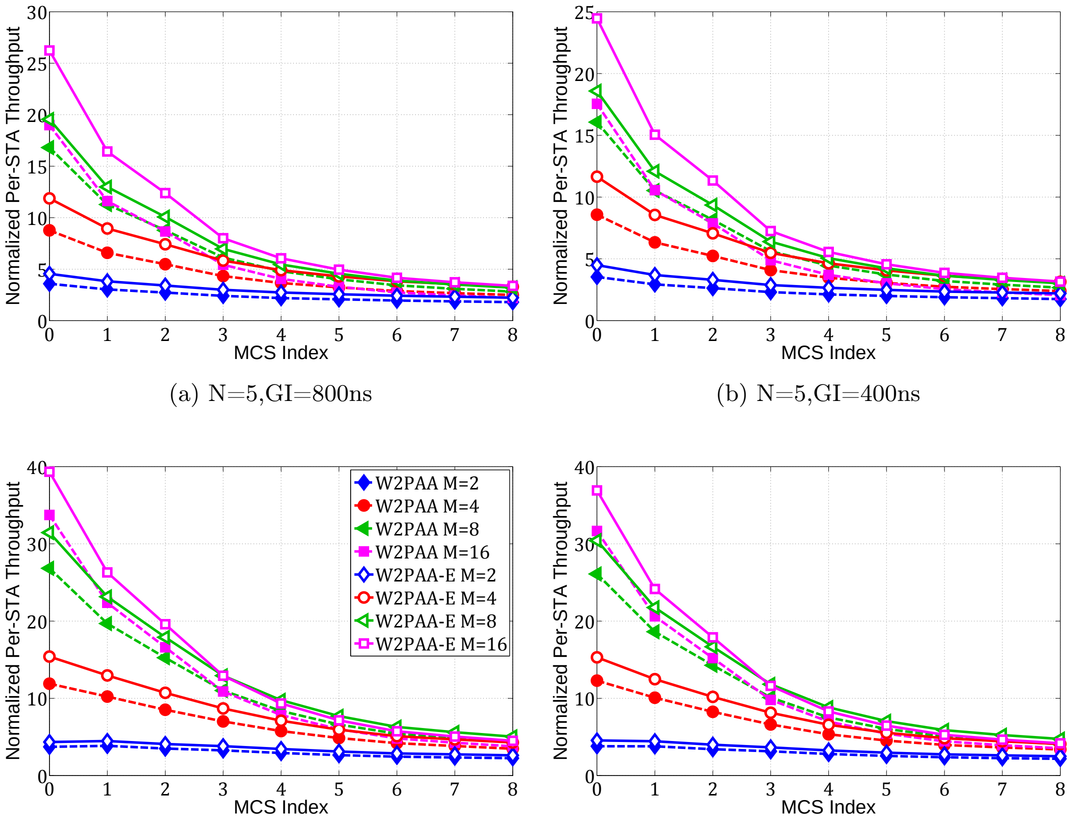
(c) N=10,GI=800ns (d) N=10,GI=400ns

Figure 4.17: Average Delay versus Channel Bandwidth

throughput to the AP in current RF conditions. In this context, network planners should be aware of deployment environment characteristics in order to choose the AP that best maximize end users throughput.

figure 4.19 shows the normalized BSS throughput as a function of MCS indexes. As observed, the normalized system throughput also declines when higher data rates are used. As for the per-STA throughput, the perceived impact of UL-MU schemes is lower since UL-SU is already enhanced by the higher data rates.

figure 4.20 represents the average delay versus MCS indexes. The average delay is enhanced for high MCS indexes. Actually when using high data rates, the propagation time over the link is reduced, and the experienced delays by data frames are reduced too. The brought enhancements to average delay are more noticeable for AP allowing smaller number of UL simultaneous transmissions. Actually, the



(a) N=5,GI=800ns

(b) N=5,GI=400ns

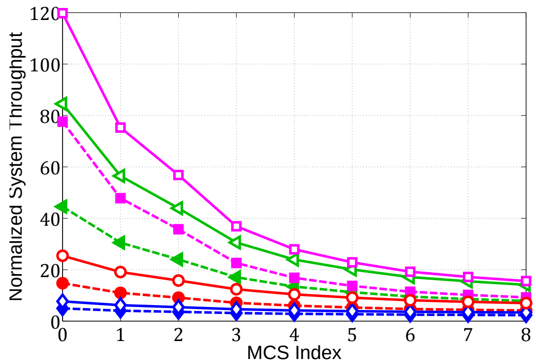
(c) N=10,GI=800ns

(d) N=10,GI=400ns

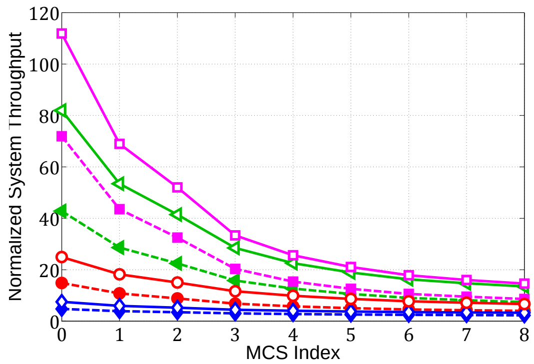
Figure 4.18: Normalized Per-STA Throughput versus MCS Index

average delay is dramatically decreased for $M = 2$ as data rates become higher; the maximum value $M = 16$ permits almost a fixed average delay whatever the MCS index is. In system using dynamic rate adaption, it is recommended to invest in many antennas in the AP in order to get less packet delays and stable behavior for different data rates.

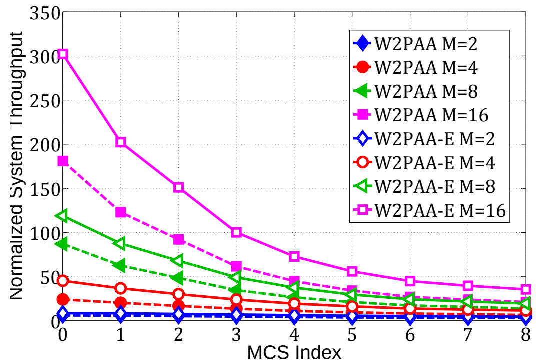
Short GI yields to lightly lower performance for both normalized per-STA and BSS throughput values, but higher performance for average delay. Indeed, the short GI implies higher data rates by 11% compared to long GI; the GI length trade-off discussed for channel bandwidth impact has to be managed in this case too.



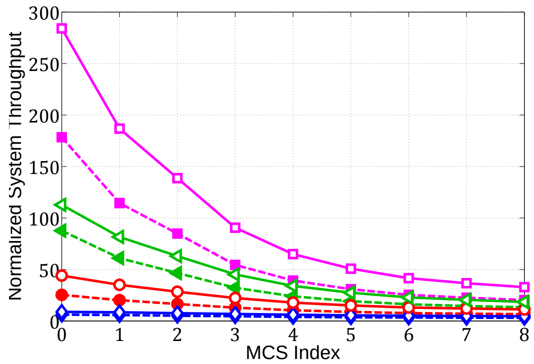
(a) N=5,GI=800ns



(b) N=5,GI=400ns



(c) N=10,GI=800ns



(d) N=10,GI=400ns

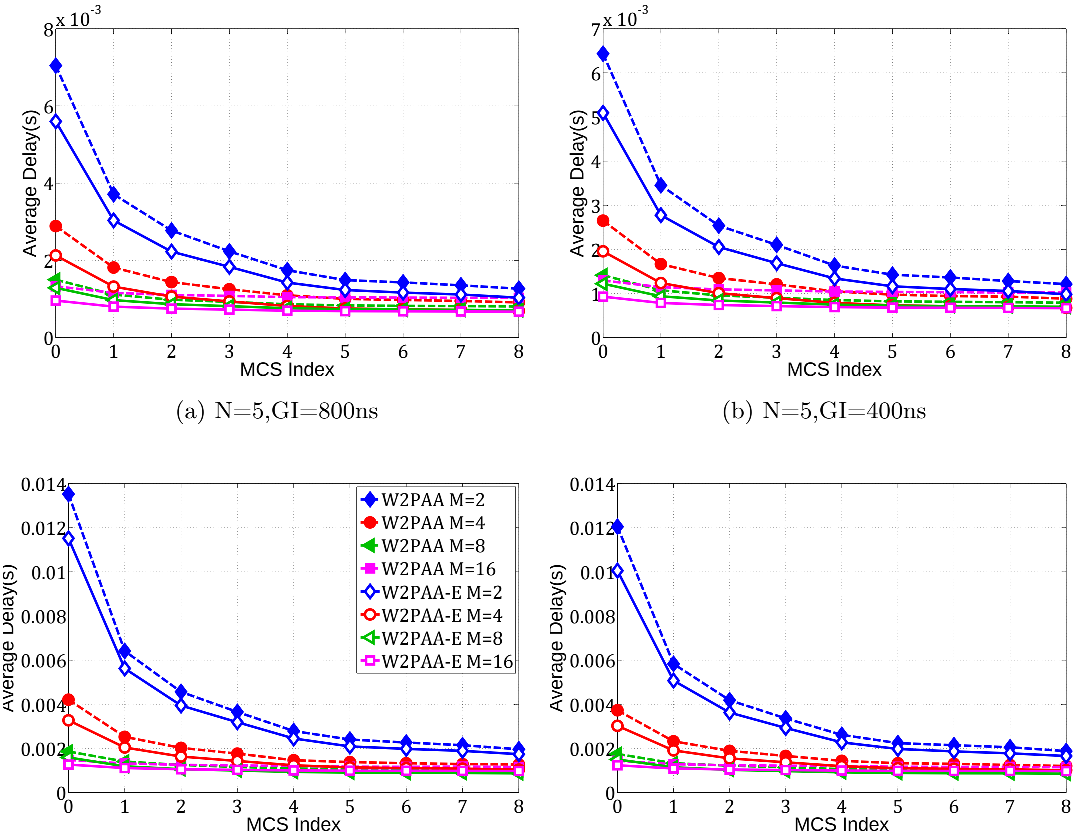
Figure 4.19: Normalized System Throughput versus MCS Index

Table 4.1: Simulations parameters

Parameter	Value
AP antennas M	1, 2, 4, 8, 16
STAs antenna	1
STA-AP distance	5m
AP TX Power	20dBm
STA TX Power	20dBm
AP antenna gain	0dBi
STA antenna gain	0dBi
Log-Normal shadowing standard deviation	5dB
Frequency	5GHz
Channel bandwidth	20MHz
Gard Interval	800ns
TxRxTurnaroundTime	2us
CCA Time	4us
Aggregation	No
MSDU length	4000 Bytes
CW_{min}	15
CW_{max}	1023
$CWmu_{min}$	1
$CWmu_{max}$	31
MAC overhead	320bits
PHY header duration	40us
Basic rate R_C	MCS0
Data rate R_D	MCS8
RTS	160 bits/ $R_C + T_{PHY}$
CTS, G-CTS	[112 bits, (112 + 48*(k-1)) bits]/ $R_C + T_{PHY}$
ACK, G-ACK	[112 bits, (112 + 48*(k-1)) bits]/ $R_C + T_{PHY}$
time slot σ	9us
SIFS	16us
DIFS	SIFS + 2*σ
λ	50

Table 4.2: Significant Percentiles of Per-STA Throughputs (Mbps)

UL mode	5th	50th	95th
SU	1.8302	4.7407	37.0070
W2PAA, M=2	6.0335	11.6235	46.7470
W2PAA, M=4	11.6478	20.0472	55.2886
W2PAA, M=8	16.8986	26.2013	47.8285
W2PAA, M=16	17.6894	24.4081	34.1072
W2PAA-E, M=2	6.2696	13.1714	54.3557
W2PAA-E, M=4	13.1203	23.5568	62.0874
W2PAA-E, M=8	18.4392	28.9588	70.6868
W2PAA-E, M=16	19.0013	26.0639	75.9504



(a) N=5,GI=800ns

(b) N=5,GI=400ns

(c) N=10,GI=800ns

(d) N=10,GI=400ns

Figure 4.20: Average Delay versus MCS Index

4.5 Conclusion

In this chapter, we proposed two novel mechanisms that enhance the UL-MU scheduling protocol for WLAN. The main principle of both versions of this protocol is to introduce a waiting time in the AP to allow the selection of stations that will be involved in the UL-MU transmission. The mean contribution of this scheme is that contention stage is performed as in legacy SU transmission, but allowing data frames to be simultaneously transmitted to the AP. This ensures a backward compatibility and hence facilitates the implementation of this scheme in future standards. Those enhancements are validated by analytical model as well as custom made simulations and compared to legacy version and SU mode. Specific performance metrics and simulations parameters are carefully chosen to best meet the currently developed IEEE 802.11ax standard.

The obtained results showed how W2PAA-E outperforms W2PAA for different network sizes, channel bandwidths and data rates. The best number of AP antennas that globally offers best performance regarding considered metrics is $M = 16$; although the per-STA throughput maximum value fluctuates for $M = 16$ and $M = 8$. Depending on what is prioritized when deploying a Wi-Fi network, either system or user performance, the number of antennas used in the AP can be adjusted or enabled/disabled when necessary.

Conclusion and Perspectives

Conclusions

In this thesis, we focused on addressing broadband services access issues in green-filed areas when totally relying on small cells technologies. Specifically, we performed analysis, modelling and optimization of the small cells access/backhaul network. The aim is to enable access to broadband services at satisfactory quality of service while keeping in mind the crucial role that play incurred costs by small cells deployments. After presenting the fundamental aspects of the small cells networks as a background for our work, we addressed the following issues.

First, we targeted the problem of choosing the most suitable backhaul solutions, including technologies and aggregation nodes, which incur the minimalist installation cost. We considered a set of small cells that are intended to serve a specific area; locations of small cells are already defined by radio planning process. We proposed then a cost-optimal model expressed as an optimization problem. This problem aims at minimizing the backhaul connections cost while abiding by technologies characteristics and network traffic constraints. An access small cells network may be backhauled differently depending on the allowed technologies by operator strategy, and may then have different connections solutions.

Traffic demand of a targeted service area drives the capacity of selected backhaul solutions. As a matter of fact, this traffic demand should be quantified to make efficient and scalable small cells deployment. It would assess the amount of traffic going from the core network to end user via the access small cell, and vice versa. For this reason, we analyzed the traffic carried by a SC backhaul segment. Actually, we divided up the backhaul pipeline into many components by respect to two criteria: 1) their carrying on S1 or X2 interfaces, and 2) the information type they carry: user or control packets. In parallel, we classified the throughput of an average user equipment into portions according to the same criteria, and we allocated a participation percentage to each portion. We then modeled the behavior of generated throughput on both logical interfaces (S1 and X2) of a single small cell via a Markov chain. This model took into consideration the impact of end users activity on small cells connection interfaces.

In the end, we concentrated our interest on Wi-Fi uplink capacity enhancement. As an attractive wireless backhaul solution for any type of small cells technology (cellular or WLAN based), Wi-Fi links should support symmetrical downlink/uplink throughput performance. Additional techniques like multi-users transmissions may be added to reach desired capacity. From this perspective, we identified and analyzed the technical issues of uplink MU-MIMO. We then designed a new MAC scheduling protocol that aims at reducing overhead messages generated by both multiple transmitters and receiver to establish this transmission. We derived this protocol into two versions: basic and enhanced. Afterwards, we modeled the basic version using a semi-Markov model to evaluate system performance. Lastly, we conducted various simulations to ascertain the high efficiency brought by conceived UL MU-MIMO scheme.

The most relevant findings of our analysis, modeling and simulations works are recapped in what follows.

- **Backhaul cost optimization:**
  - ◦ Wireless solutions are far and away the less costly when used for backhauling an access small cells network. This corroborates MNOs business strategy to adopt more wireless solutions.
  - ◦ The backhaul cost gap between wireless and wired solutions is increasing as the network becomes larger: wireless links are economically more advantageous for scalable networks.
  - ◦ Wireless backhaul meet aggregation capacity requirements when bandwidth access need increases; indeed, wireless backhaul is adjustable to access demand, the incurred costs are then tuned to the evolution of actual bandwidth consumption.
  - ◦ Larger range small cells are very recommended, since it lowers the needed

number of aggregation links to the PoC.

- ◦ Wireless backhaul requires low levels of operator presence: the generated linking cost is thinly affected by the available operator PoCs. This enables huge installation cost savings: PoCs are generally high level processing nodes, then cost important CAPEX and OPEX; and they require very high capacity links to be connected to the core network (namely based on wired technologies: e.g. fiber).

- **Traffic analysis for a 4G small cell:**
  - ◦ Small cells with higher capacity experience higher throughput, in both S1 and X2 interfaces. However, S1 throughput is extensively impacted whereas X2 throughput increases slowly. This confirms how S1 traffic is predominated by user plane traffic.
  - ◦ UEs activity has a very low impact on X2 throughput, whereas S1 throughput rises enormously with highly active UEs. The estimation of access network traffic profiles would help to recommend suitable backhaul links.
  - ◦ UEs activity does not decline the small cell capability to process new arriving UEs, it even enhances it. This capability is even enhanced when the small cell has higher capacities. This means that as soon as end users traffic is carried properly, there are served quickly and don't retain small cell resource for long time.

- **UL MU-MIMO for capacity enhancement in WLAN:**
  - ◦ Globally, the proposed W2PAA-E outperforms both SU UL scheme and W2PAA. Both user and system performance are enhanced when using it. The most relevant metrics, as targeted by TGax, are fulfilled: average delay, per-user throughput and BSS throughput.
  - ◦ The best achievable average delay and BSS throughput performances are proportional to AP antennas number. However, the per-user throughput has the most enhanced values for both 8 and 16 antennas AP, depending on network size. It is recommended to equip the AP with 8 antennas: this provides a quite high performance while reducing AP equipment cost and processing complexity.

◦ The MAC efficiency, measured by MAC latency, is the best improved with W2PAA-E scheme.

◦ Even it does not reach SU scheme performance, the packet re-transmission ratio is the lowest with W2PAA-E.

◦ W2PAA exhibits the fairest share of the channel, while W2PAA-E has a varying fairness index depending on used antennas on the AP. The fairness should be more investigated in multi-rates transmissions.

◦ The added value with W2PAA-E (and partially W2PAA) to average delay, per-user throughput and aggregated throughput performances decreases as the channel bandwidth is larger. In fact, larger channel bandwidths allow already better performance, so the impact of UL MU schemes is less noticeable for those cases. The same finding is valid when the system (AP and stations) uses high data rates.

Perspectives

Finally, herein we highlight some open questions and perspectives for future work.

- **Small Cells Backhaul:**

◦ We provided a cost-optimization model that minimizes linking cost based on individual links costs. The costs we considered in this dissertation represent a cost/link; nonetheless, not all backhaul technologies have the same cost structure: there are many components that drive this cost (as introduced in Chapter 1). It would be more interesting to consider a cost modeling approach that provides the most accurate cost per technology. The obtained costs will be injected to the optimization model for more precise linking solutions. The injected costs may be scalar values or functions (depending on certain characteristics like distance between nodes, capital depreciation rate, etc).

◦ Some of the considered wireless solutions have low ranges (e.g. Wi-Fi) even they provide high capacity. It would be valuable to consider adding relay nodes where the optimization model fails to aggregate a link due to range constraint, more specifically, in cases the allowed wireless solutions by the operator is restrained.

  - In this thesis, we focused on specific requirements of small cells backhaul with green-field use case. Other requirements should be investigated, either with centralized approaches on each item, or multi-objective approaches.

- **Traffic Impact on Small Cells green-field deployments:**

  - In the Markov model designed to analyze UE activity impact on logical interfaces of small cells, we focused only on the behavior of a single small cell. Although X2 signalization traffic was allotted a certain ratio in the overall UE throughput, it was not accurately evaluated. It would be suggested to extend the model to implicate many small cells interaction in the same time. This would provide better understanding of the real impact of users activity on carried small cells throughput.

  - We divided up the UE throughput into components depending on whether it goes throughout S1 or X2 interfaces of the small cell, and whether it belongs to data traffic or signalization messages. The UE throughput may be disassembled according to additional criteria, like type of carried data traffic: voice over IP, web browsing, video streaming, etc, and their QoS requirements. Hence, defining different traffic profiles would enable to properly select the backhaul solutions that most fit access QoE requirements.

- **WLAN capacity enhancements:**

  - We proposed a MAC scheduling scheme for UL MU-MIMO transmissions in WLAN. This protocol ensures high system and user oriented performance. Simulation framework considered perfect channel conditions. It would be useful to evaluate its performance in non-ideal environments, and to define precisely its implementation in the physical layer of WLAN equipments.

  - We evaluated W2PAA-E (and W2PAA) with fix parameters throughout conducted simulations. More dynamic networks -with varying packet sizes, multi-rates transmissions and packet generation rates- should be considered to get a complete view on its achievable performance.

  - The IEEE 802.11 working groups are not yet ready to introduce standalone

UL MU-MIMO transmissions in future standards. They first forecast UL MU-MIMO TXOP to be managed with/after a DL MU-MIMO TXOP. Some insights may be provided in this optic: an upgraded W2PAA-E may be combined with existing DL MU-MIMO schemes to ease its insertion.

Appendix A

Performance measures computing

In this annex, we compute the transmission probability, the holding times for each state of the semi-Markov chain, the system throughput and the average delay; all those values are obtained for both SU and W2PAA schemes.

A.1 Transmission Probability

Figure 4.2 depicts all the transition probabilities, from which stationary probabilities are derived: $\pi_{(i,k)} = \lim_{t\to\infty} P(s(t) = i, b(t) = k)$ where $i \in [0, m]$ and $k \in [0, W_i-1]$. They are expressed as follows in equations (A.1)):

$$\begin{cases} \pi_{I^-} & = p\,\pi_{(m,0)} \\ \pi_{I^+} & = (1-p)\,\pi_{(m,0)} \\ \pi_{(0^-,k)} & = \frac{p}{W}\,\pi_{I^-} + \pi_{(0^-,k+1)} \qquad k \in [0, W-2] \\ \pi_{(0^-,W-1)} & = \frac{p}{W}\,\pi_{I^-} \\ \pi_{(0^+,k)} & = \frac{1-p}{W-1}\,\pi_{I^+} + \pi_{(0^+,k+1)} \qquad k \in [0, W-3] \\ \pi_{(0^+,W-2)} & = \frac{1-p}{W-1}\,\pi_{I^+} \\ \pi_{(1,k)} & = \frac{p}{W_1}\,\pi_{(0^+,0)} + \frac{p}{W_1}\,\pi_{(0^-,0)} + \pi_{(1,k+1)}\; k \in [0, W_1-2] \\ \pi_{(1,W_1-1)} & = \frac{p}{W_1}\,\pi_{(0^+,0)} + \frac{p}{W_1}\,\pi_{(0^-,0)} \\ \pi_{(i,k)} & = \frac{p}{W_i}\,\pi_{(i-1,0)} + \pi_{(i,k+1)} \qquad i \in [2, m];\ k \in [0, W_i-2] \\ \pi_{(i,k)} & = \frac{p}{W_i}\,\pi_{(i-1,0)} \qquad i \in [2, m] \end{cases} \tag{A.1}$$

Precedent stationary probabilities are simplified to equations (A.2) by considering $\pi_{(0,0)} = \pi_{(0^-,0)} + \pi_{(0^+,0)}$:

$$\begin{cases} \pi_{I^-} & = p^{m+1}\, \pi_{(0,0)} \\ \pi_{I^+} & = (1-p)\, p^{m+1}\, \pi_{(0,0)} \\ \pi_{(i,0)} & = p^i\, \pi_{(0,0)} \qquad i \in [1,m] \\ \pi_{(i,k)} & = \frac{W_i - k}{W_i}\, \pi_{(i,0)} \qquad i \in [1,m];\ k \in [0, W_i - 1] \\ \pi_{(0^-,k)} & = \frac{W-k}{W}\, \pi_{(0^-,0)} \qquad k \in [0, W-1] \\ \pi_{(0^+,k)} & = \frac{W-k-1}{W-1}\, \pi_{(0^+,0)} \qquad k \in [0, W-2] \\ \pi_{(0^-,0)} & = p^{m+2}\, \pi_{(0,0)} \\ \pi_{(0^+,0)} & = (1 - p^{m+2})\, \pi_{(0,0)} \end{cases} \tag{A.2}$$

The normalization condition of the semi-Markov chain is expressed in equation (A.3):

$$\sum_{\textit{All States}} \pi = 1 \tag{A.3}$$

Equation (A.3) implies:

$$\pi_{(0,0)} = 1 \Big/ \left[\frac{1}{2} \sum_{i=1}^{m} p^i \left(2^i W + 1\right) + \frac{p^{m+2} + W}{2} + p^m \right] \tag{A.4}$$

The probability τ that a station transmits in a randomly chosen time slot is:

$$\tau = \sum_{i=1}^{m} \frac{P_i}{h_i} + \frac{P_{0^-}}{h_{0^-}} + \frac{P_{0^+}}{h_{0^+}} \tag{A.5}$$

Where P_i is the proportion of time that a STA is at $S(i,0)$, $i \in [0^-/0^+, m]$ and h_i the expected state holding time for state $S(i,0)$, $i \in [0^-/0^+, m]$.

Let T be time spent by the STA in all states, then:

$$P_i = \frac{\pi_{(i,0)}\, h_i}{T} \tag{A.6}$$

$$h_i = p\, \overline{T_c} + (1-p)\, \overline{T_s} = h = h_{0^-} = h_{0^+} \tag{A.7}$$

Where $\overline{T_c}$ is the average time the channel experiences a collision and $\overline{T_s}$ is the average time the channel is sensed busy because of successful transmission.

T is expressed as follows (equation (A.8)):

$$T = \sum_{All\ States} \text{Stationary probability of state S} \times \text{State holding time for state S} \tag{A.8}$$

The probability τ is finally expressed as in equation (A.9):

$$\tau = \frac{\sum_{i=1}^{m} p^i + 1}{\frac{p^m}{\lambda} + \frac{1}{2}\sum_{i=1}^{m} p^i \left(2^i W + 1\right) + \frac{p^{m+2}+W}{2} + h\left(\sum_{i=1}^{m} p^i \ + 1\right)} \tag{A.9}$$

Let p_{su} be the collision probability and τ_{su} transmission probability for UL-SU transmission:

$$p_{su} = 1 - (1 - \tau_{su})^{N-1} \tag{A.10}$$

Let p_{mu} be the collision probability and τ_{mu} transmission probability for W2PAA transmission. For W2PAA, only RTS frames contend for channel access and hence are the only frames that may be impacted by collisions. Once a RTS frame is successfully transmitted, the associated data frame has no risk to encounter a collision. Consequently, the relation between p_{mu} and τ_{mu} is expressed the same for UL-SU transmission:

$$p_{mu} = 1 - (1 - \tau_{mu})^{N-1} \tag{A.11}$$

The equations systems $\{$(A.9), (A.10)$\}$ and $\{$(A.9), (A.11)$\}$ are solved for UL-SU and W2PAA respectively to obtain $(p_{su},\ \tau_{su})$ and $(p_{mu},\ \tau_{mu})$. The main difference between SU and W2PAA solutions is the expression of holding times: the latter depend on the average time the channel is sensed busy because of a successful transmission and average time the channel is sensed busy because of packet collision. Those components are computed in next subsection for both SU and W2PAA schemes.

A.2 Holding time components

We refer to the expression of holding time in equation (A.7). We assume that all packets have fixed payload size L. Let L_{MAC} be the MAC header length (bits),

R_D be the data rate, T_{PHY} be the PHY header length (s), R_C be the channel bit rate and δ be the propagation delay. In the following expressions, RTS, CTS, ACK, G_CTS and G_ACK refer respectively to required times to transmit RTS, CTS, ACK, G-CTS and G-ACK frames. σ denotes the empty time slot. δ is the propagation delay.

Let T_s^{SU} and T_c^{SU} be the average time of a successful transmission and the average time of packet collision for UL-SU. T_s^{SU} and T_c^{SU} are detailed in (A.12):

$$\begin{cases} T_s^{SU} &= RTS + SIFS + \delta + CTS + SIFS + \delta + \frac{L_{MAC}}{R_D} + \\ & \quad T_{PHY} + \frac{L}{R_D} + SIFS + \delta + ACK + DIFS + \delta \\ T_c^{SU} &= RTS + DIFS + \delta \end{cases} \tag{A.12}$$

Let $\overline{T_s^{SU}}$ and $\overline{T_c^{SU}}$ be the average time that the channel is sensed to be busy because of a successful transmission and the average time that the channel is sensed to be busy because of packet collision for UL-SU. $\overline{T_s^{SU}}$ and $\overline{T_c^{SU}}$ are detailed in (A.13):

$$\begin{cases} \overline{T_s^{SU}} &= T_s^{SU} + \sum_{t=1}^{\infty} (\frac{1}{W})^t \times T_s^{SU} + \sigma \\ &= T_s^{SU} \frac{W}{W-1} + \sigma \\ \overline{T_c^{SU}} &= T_c^{SU} + \sigma \end{cases} \tag{A.13}$$

For W2PAA transmission, we introduce T_{sj}^{MU}, the average time slot needed for a successful simultaneous transmission of j packets. T_{sj}^{MU} is expressed in (A.14):

$$\begin{aligned} T_{sj}^{MU} =& j * RTS + (j-1) * DIFS + j * \delta + SIFS + G\_CTS + SIFS + \delta + \frac{L_{MAC}}{R_D} \\ &+ T_{PHY} + \frac{L}{R_D} + SIFS + \delta + G\_ACK + DIFS + \delta \end{aligned} \tag{A.14}$$

Let $\overline{T_{sj}^{MU}}$ be the average time slot during which the channel is sensed busy for a successful simultaneous transmission of j packets. It is expressed in (A.15):

$$\overline{T_{sj}^{MU}} = T_{sj}^{MU} \frac{W}{W-1} + \sigma \tag{A.15}$$

Let T_c^{MU} the average time of packet collision in W2PAA (equation (A.16)):

$$T_c^{MU} = RTS + DIFS + \delta \tag{A.16}$$

Consequently, $\overline{T_s^{MU}}$, the average time slot length during which the channel is busy of successful simultaneous transmission, and $\overline{T_c^{MU}}$ the average time that the channel is sensed to be busy because of packet collision in simultaneous transmission mode are expressed in (A.17):

$$\begin{cases} \overline{T_s^{MU}} & = \frac{\sum_{j=1}^{K} \overline{T_{sj}^{MU}}}{K} \\ \overline{T_c^{MU}} & = T_c^{MU} + \sigma \end{cases} \tag{A.17}$$

A.3 Throughput

Let S_{su} and S_{mu} be the system throughput for SU and W2PAA respectively, it is the ratio of payload data bits transmitted and the duration of time spent to successfully transmit this payload, P_{tr} be the probability that there is at least one transmission in the considered time, P_s^{SU} and P_s^{MU} be the probabilities that a transmission occurring on the channel is successful in SU and MU transmissions respectively:

$$P_{tr} = 1 - (1 - \tau)^N \tag{A.18}$$

$$P_s^{SU} = \frac{N\tau(1-\tau)^{N-1}}{P_{tr}} \tag{A.19}$$

$$P_s^{MU} = \sum_{j=1}^{K} P_{sj} = \sum_{j=1}^{K} \frac{\binom{N}{j}\tau^j(1-\tau)^{N-j}}{P_{tr}} \tag{A.20}$$

Where P_{sj} is the probability that j simultaneous packet transmissions among N are successful, conditioned on the fact at least one station transmits:

$$P_{sj} = \frac{\binom{N}{j}\tau^j(1-\tau)^{N-j}}{P_{tr}} \tag{A.21}$$

Let $\overline{L}$ be *the average payload size accounting for multiple frames transmitted into a time slot.* $\overline{L}$ is detailed in equation (A.22).

$$\overline{L} = L + \sum_{t=1}^{\infty}(\frac{1}{W})^t \times L = L\,\frac{W}{W-1} \tag{A.22}$$

Finally, system throughput is expressed for both SU and W2PAA transmissions:

$$S_{SU} = \frac{P_{tr}\,P_s^{SU}\,\overline{L}}{(1-P_{tr})\sigma + P_{tr}P_s^{SU}\overline{T_s^{SU}} + P_{tr}(1-P_s^{SU})\overline{T_c^{SU}}} \tag{A.23}$$

$$S_{MU} = \frac{\sum_{j=1}^{K} j\,P_{sj}\,P_{tr}\overline{L}}{(1-P_{tr})\sigma + \sum_{j=1}^{K} P_{tr}P_{sj}\overline{T_{sj}^{MU}} + P_{tr}(1-P_s^{MU})\overline{T_c^{MU}}} \tag{A.24}$$

A.4 Average Delay

Delay is defined as time interval from the instant a packet is at the Head of Line (HOL) of its MAC queue, ready to be transmitted, and the instant acknowledgment frame for this packet is received. Average delay D is the average value of this interval for all transmitted packets. Indeed, average access delay is computed following the same analysis in [11]. By using Little's law, the long term average number of contending stations that will deliver successfully their HOL packets N^* is equal to the long term average effective packet delivery rate R_P multiplied by the average time –i.e. average access delay- D a packet experiences before being delivered. Algebraically speaking, it means:

$$D = \frac{N^*}{R_P} = \frac{N^*\,\overline{L}}{S} \tag{A.25}$$

As the backoff time countdown is assumed to have a uniform distribution in the interval [0, Wi], then for stage i, $E[b(t)] = Wi/2$. Average delay is then expressed:

$$D = \frac{\overline{L}N}{S} \times \left[1 - \frac{p^{m+1}\,\pi_{(0,0)}}{2}\left[\sum_{i=1}^{m}(W_i+1)\ + p^{m+1}(W+1) + Wp^m(1-p)\right]\right] \tag{A.26}$$

We replace (τ, p, S) by (τ_{su}, p_{su}, S_{su}) and (τ_{mu}, p_{mu}, S_{mu}) to get the average delays for SU and MU respectively.

Publications

Peer-reviewed journal paper

Btissam Er-Rahmadi, Adlen Ksentini, and Djamal-Eddine Meddour, "Enhanced Uplink Multi-Users Scheduling for Future 802.11ax Networks: Wait-to-Pick-As-Available Enhanced (W2PAA-E)", Wiley WCMC (accepted for publication).

International conferences with peer review

Btissam Er-Rahmadi, Adlen Ksentini, and Djamal-Eddine Meddour, "New backhaul approach for small cells based coverage in green-field deployments," in Global Information Infrastructure and Networking Symposium (GIIS), Montreal, Canada, 2014.

Btissam Er-Rahmadi, Adlen Ksentini, and Djamal-Eddine Meddour, "Wait-to-pick-as-available (W2PAA): A new MAC protocol for uplink multi-users transmissions in WLAN," in IEEE 11th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Abu-Dhabi, UAE, 2015.

Btissam Er-Rahmadi, Adlen Ksentini, and Djamal-Eddine Meddour, "A Traffic-Driven Analysis for Small Cells Backhaul Planning," in IEEE Wireless Communications and Networking Conference (WCNC), Doha, Qatar, 2016.

Btissam Er-Rahmadi, Miloud Bagaa, Adlen Ksentini, and Djamal-Eddine Meddour, "Cost-Efficient Data Aggregation Schemes for Small Cell Networks," in 12th International Wireless Communications and Mobile Computing Conference (IWCMC), Paphos, Cyprus, 2016.

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