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## **Techno-economical Analysis of Indoor Enterprise Solutions**

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*Publication date:*  
2013

*Document Version*  
Accepted author manuscript, peer reviewed version

[Link to publication from Aalborg University](#)

*Citation for published version (APA):*  
Liu, Z. (2013). *Techno-economical Analysis of Indoor Enterprise Solutions*.

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# Techno-economical Analysis of Indoor Enterprise Solutions

PhD Thesis

by

Zhen Liu



A dissertation submitted to  
Department of Electronic Systems,  
the Faculty of Engineering and Science, Aalborg University  
in partial fulfillment for the degree of  
Doctor of Philosophy,  
Aalborg, Denmark  
December 2013.

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ISBN: 978-87-7152-025-5

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# Abstract

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The rapid growth of high-data-rate applications along with the fact that the majority of mobile data traffic is originated indoor has drawn much attention on In-building Wireless (IBW) solutions, from industry to academic research. The Mobile Network Operator (MNO)s seek proper indoor solutions to accommodate the high indoor traffic demand for their future network evolution. In this thesis, we study the dedicated indoor systems for enterprise solutions of interest to the MNOs.

The Distributed Antenna System (DAS) and Femtocells constitute two major IBW solutions for efficient in-building coverage extension and capacity provision. This study makes a technology economical examination based on these two systems for network evolution using the Long Term Evolution (LTE) technology. We first evaluate their radio performance for indoor high-data-rate deployment, and propose a centralized coordinated scheduling system to improve performance. Afterwards, the system cost analysis is conducted and compared between systems in distinctive applications.

The performance is evaluated based on simulations. Overall, the DAS is less efficient in providing high speed, high volume mobile data services than the multi-cell system, i.e. the Femto system and the proposed centralized coordinated scheduling system. The proposed system is proved capable of achieving the best overall performance while the performance being robust and unaffected by non-optimal Access Point (AP) placement. In fully loaded networks, the un-coordinated Femto system performance is largely deteriorated due to heavy inter-cell interference. A Quality-Guaranteed (QG) scheduler is developed to improve the cell edge user experience and increase the number of supported QoS users (by enforcing the base station to allocate more radio resources to cell edge users). Further improvement of the performance can be achieved by adopting interference avoidance schemes,

which is also studied in this thesis. Outside the busy hours, the network is normally partially loaded and the multi-Femto system demonstrates much higher capacity compared to the DAS.

Subsequently, we conduct the financial economic analysis for indoor DAS and Femto systems based on the total cost of ownership (TCO) analysis. The TCO is a financial estimate to determine the direct and indirect costs of a product or a system over a certain time period. For very high data-rate in-building deployment, the Femto system has absolute advantage compared to the DAS. For coverage-oriented deployment with very limited user data traffic demand, DAS is the most economical solution in large-size buildings, and Femto is more economical for deployment in small-size buildings. This decision of which system to deploy is made based on many factors such as the Femto Access Point (FAP) price, the existence of an old DAS, the share of the DAS among multiple operators and even the market labor cost. The extend of cost saving is also highly influenced by the availability of the backhaul connectivity: from the cost point of view, it is less critical which of the two systems to choose when the backhaul cost becomes the dominant part of the TCO. For all the factors, detailed analysis is made and suggestions given according to different scenarios. It can be concluded that the vast adoption of enterprise Femtocells will start in indoor hotspots with high data traffic demand and high capacity backhaul accessible at minor cost.

# Dansk Resumé<sup>1</sup>

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Den hurtige vækst i høj data-rate applikationer sammen med det faktum, at mest mobile datatrafik er opstået indendørs, har trukket meget opmærksomhed på In-building Trådløs (IBW) løsninger, fra industrien til akademisk forskning. Den Mobile Network Operator (MNO) søger gode indendørs løsninger for at imødekomme den store efterspørgsel efter den høje indendørs trafik til deres fremtidige net udvikling. I denne afhandling studerer vi de dedikerede indendørs systemer for virksomhedsløsninger af interesse for MNO'er.

Det Distributed Antenna System (DAS) og Femtoceller udgør to store IBW muligheder for en effektiv udvidelse af indendørs dækning og tilstrækkelig kapacitet. Dette studium laver en teknisk-økonomisk undersøgelse baseret på disse to systemer til indendørs netværkudvikling frem mod Long Term Evolution (LTE).

Vi evaluerer først resultaterne af de indendørs systemer med simulering. Samlet set er DAS mindre effektiv i at yde mobile datatjenester med høj hastighed og høj volumen end multi-cellesystemet, dvs. Femto systemet og det foreslåede system. Det er bevist, at det foreslåede centraliserede, koordinerede planlægningsystem er i stand til at opnå den bedste samlede ydeevne, mens resultatet er robust og upåvirket af ikke-optimal Access Point (AP) placering.

I fuldt lastede netværk bliver ydeevnen af det rene Femto-system (uden inter-Femto koordination) i vid udstrækning forringet på grund af kraftig inter-celle interferens. Den kvalitetssikrede (QG) scheduler anbefales derfor for at forbedre celle-kant brugeroplevelsen og øge antallet af understøttede QoS-brugere. Yderligere forbedring af ydeevnen kan opnås ved at vælge interferens unddragelses-ordninger. Forskellige interferens- unddragelsessystemer via MAC-lag pakkeplanlægning er

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<sup>1</sup>Translated by Jytte Larsen of Nokia Siemens Networks, Aalborg, Denmark.

blevet undersøgt. Mens hvert system er i stand til at forbedre antallet af understøttede brugere, er der imidlertid en omkostning: større følsomhed over for ikke-optimal AP placering eller reduceret system-gennemløb.

Efterfølgende foretager vi den finansielle økonomiske analyse for indendørs DAS og Femto systemer baseret på de samlede omkostninger ved ejerskab (TCO) analyse. Ved udnyttelse af meget høj data-rate i bygninger, har Femto systemet den absolutte fordel i forhold til DAS. For dæknings-orienteret udnyttelse med meget begrænset behov for bruger datatrafik er DAS den mest økonomiske løsning i store bygninger, og Femto er mest økonomisk ved brug i små bygninger. Den fordeling af bygnings-størrelse, der afgør, om DAS eller Femto systemet skal bruges, afhænger af mange faktorer, såsom prisen på Femto Access Point (FAP), eksistensen af en gammel DAS, andelen af DAS mellem flere operatører og selv markedets lønomkostninger. Omfanget af besparelser bestemmes også af tilgængeligheden af backhaul-forbindelse. For alle faktorerne er der lavet en detaljeret analyse og givet forslag i henhold til forskellige scenarier.

# Preface and Acknowledgments

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This PhD thesis is the result of a three-and-half-year research project carried out at the Radio Access Technology (RATE) section, Institute of Electronic Systems, Aalborg University, Denmark. The thesis work has been completed in parallel with the mandatory courses and teaching/working obligations required in order to obtain the PhD degree. The research project has been completed under the supervision and guidance of Associate Professor Troels B. Sørensen (Aalborg University), and Professor Preben E. Mogensen (Aalborg University, Nokia Siemens Networks, Aalborg, Denmark). It has been co-financed by the Faculty of Engineering, Science and Medicine, Aalborg University (1/2), and Nokia Siemens Networks, Aalborg (1/2).

The thesis investigates in-building small cell technologies to complement the wide area network for providing cost-efficient high data rate services. The chapters in the thesis fall into two parts, where the first part deals with the system performance, and the second part addresses the cost aspects.

I would like to thank my supervisor Dr. Troels B. Sørensen and Dr. Preben E. Mogensen, who has given me so much patience and support throughout my three years' study. Without their help, I could not have completed this work. I would never forget how you encouraged me during the days that I got so frustrated at work and became pessimistic towards everything. As many other professors 'supervise' their students, they take care of their students.

I am also thankful to my colleagues in the RATE group and Nokia Siemens Networks, Aalborg. In particular, thanks to Dr. Jeroen Wigard for his guidance on the simulation and how to make better presentations; thanks to Dr. István Kovács, Frank Frederiksen and Dr. Troels Kolding for the prompt and accurate answers; and thanks to all the nice Chinese/Italian/Spanish/Brazilian/Danish friends in



Aalborg, I love you all.

I am also deeply thankful to our section secretary Lisbeth Schiønning Larsen for the friendly assistance with administrative issues, and Jytte Larsen, the secretary of Nokia Siemens Networks (Aalborg site), for the proofreading of my papers and this thesis.

Dr. Yuanye Wang thanked me in his Ph.D thesis in 2010 as being a kind girlfriend of his. Now, as his ex-girlfriend, I would like to express my thanks to him for being a perfect husband for over two years.

Finally, special thanks to my parents for their invaluable understanding and support for all my decisions through my life and their profound love.

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# Introduction

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## 1.1 Overview of Wireless Data Traffic Situation

### 1.1.1 Current Wireless Data Traffic Usage

Ever since the introduction of the First Generation (1G) wireless communication systems in the early 1980s [1], the wireless communication systems have continuously evolved to provide more, and better services to the end users. Along with the basic feature of voice connectivity, the current wireless systems can now provide users with a variety of multi-media services, e.g. voice over IP (VoIP), streaming, web surfing, file sharing [2, 3]. The wireless data traffic has overtaken the voice traffic at the end of 2009, and it continuously grows by at least 2-fold each year [4–6]. The growth rate is even higher in some cities, e.g., Hong Kong has seen over 14-fold growth in the two year period between 2007 and 2009 [7]. Among different multi-media services, mobile video has exceeded 50% of the total data volume, followed by web browsing with about 20% share [4, 5].

The driving forces behind the data traffic growth include:

1. The commercialization of the Fourth Generation (4G) equipment:  
As reported in [4], a 4G connection generated 28 times more traffic than a non-4G connection in the year 2011.

2. The popularity of smartphones:

As compared to a basic-feature phone, a smartphone supports many multimedia services and on average generates 35 times the traffic of the former. Furthermore, the average amount of traffic per smartphone increases at a much faster speed (nearly tripled in 2011). For the United Kingdom operator O2, the launch of iPhone caused a 18-fold data traffic increase in the year 2008, i.e., traffic approximately doubled every three months [7].

3. The increasing number of wireless-connected tablets:

The number of tablets increases at a similar rate as the smartphones, and on average, each tablet generates 3.4 times more traffic than a smartphone.

4. The emergence of wireless broadband as substitution of fixed broadband:

A survey in [8] has shown a significant uptake of wireless broadband in the European market, through Universal Serial Bus (USB) dongles and Personal Computer (PC) cards. Despite the smaller number of wireless connected tablets and PCs, they constitute even more data traffic than the smartphones [4, 5].

5. The flat-rate pricing scheme:

Many operators offer flat-rate pricing to the mobile subscribers. This also has a significant impact on the data volume growth [9–11]. In fact, most of the data traffic is generated by a small portion of the users. In the year 2011, the top 1% mobile data subscribers has generated 24% of the data traffic [4]. This behavior is affected by the operators' surcharge plan for data usage over-runners.

### 1.1.2 Wireless Data Traffic Forecast

As to the future of wireless communication systems, despite the difference in the exact growth rate prediction, the consensus among operators and equipment vendors is that the explosive expansion of the wireless data traffic will still continue at a very high speed. E.g., Ericsson [5] and Analysys Mason [12] have predicted an average growth of 10-fold in the next 5 years. Cisco has an even higher prediction of 18 times growth [4], whereas Alcatel-Lucent is expecting an increase of 30 times within the same time period [13].

These predictions are based on the fact that the smartphone uptake is still low: the smartphone shipment has accounted for more than 20% of all handsets sold in the past two years [5]. However, they only represent about 12% of the total global handset volume, thus giving huge potentials for further uptake [4]. It is expected that over the coming years, the data volume will be equally split between smartphones and wireless connected tablets/PCs. Also, the mobile penetration rate and the number of wireless connected devices will continue to increase, especially in

developing countries. By 2016, one quarter of the mobile users will have more than one wireless-connected device (as compared to only 8% in 2011) and 9% will have three or even more. Furthermore, the growth in usage per device even outpaces the growth in the number of devices, by two to five times [4].

Other than the surge in data volume, another visible trend is that the user (data traffic) density will become very uneven across different places. One reason for this is the effect of global urbanization. By 2016, over 30% of the world's population is expected to live in metro and urban areas [14]. As a consequence, around 60% of the data traffic will be generated by users living on less than 1% of the Earth's total land area [5]. Furthermore, the data traffic also moves indoor. Even though most of the devices with wireless connections are portable and have the potential of accessing the network from different places, the dominant part of the traffic is still generated from inside the building [12, 15–17]. The residential area, business and commercial centers are hotspots with the dense data traffic. The ratio of indoor data traffic growth is presented in Figure 1.1, which shows that already in the year 2013, more than 80% of the traffic will be generated from indoor.

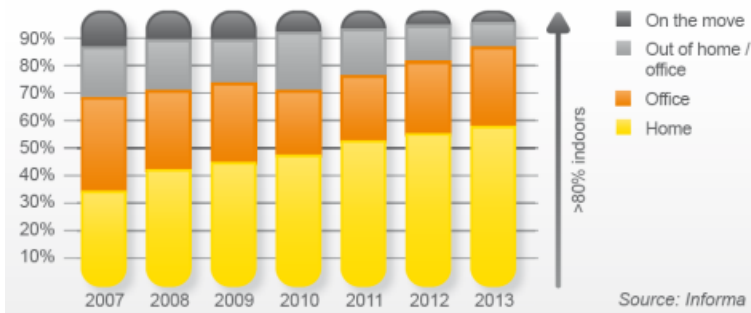


Figure 1.1: Indoor data traffic growth.<sup>1</sup>

## 1.2 Challenges to Operators' Incumbent Mobile Networks and Possible Solutions

The explosion in data traffic volume has created several challenges for the operators. The most important concerns are how to provide a satisfying Quality of Service (QoS) level for subscribers, and how to maintain a profitable margin when the revenue per bit significantly reduces. More specifically, the flat-rate scheme encourages subscribers to consume more data volume, e.g. by using more point-to-point transmission, and has posed serious challenges to mobile operators – they

<sup>1</sup>Source from Informa



cannot support the high speed offers they have been competing on if everyone starts using it [18, 19]. The three most important solutions are briefly discussed in the following.

### **Update the network technology**

The data traffic growth has outpaced the revenue growth in current wireless networks [15]. As a consequence, the operators are forced to update their technologies to reduce network cost. This motivates for the roll-out of the Long Term Evolution (LTE) systems in many countries. Using Multiple Input Multiple Output (MIMO) transmissions over a wide bandwidth of up to 20 MHz, LTE achieves a downlink peak data rate of 300 Mbps [20, 21]. This is much higher than the previous releases from 3GPP, e.g. Wideband Code Division Multiple Access (WCDMA) and High Speed Packet Access (HSPA) systems, not to mention the Global System for Mobile communication (GSM) system and their evolved versions, e.g., General Packet Radio Service (GPRS) and Enhanced Data rates for GSM Evolution (EDGE).

### **Increase the available spectrum**

Besides technology, another dominant factor for the network capacity is the spectrum. Spectrum is a scarce resource in wireless transmission, and only few bands remain available for the wireless communication systems. The International Telecommunications Union (ITU) has allocated the 2.6 GHz band for terrestrial mobile communication service [22]. This provides opportunities to increase the capacity by occupying a much wider bandwidth than the current systems. Currently, the 2.6 GHz band has been licensed in many countries, and is (or will be) under auction in some others [12, 23]. Some countries are also planning to re-farm the 900 MHz spectrum, previously allocated for Second Generation (2G) systems [12]. In Europe, the total available spectrum for Third Generation (3G) and 4G is expected to increase from 150 MHz to 470 MHz over the coming years [24]. This brings about 200% increase in capacity.

### **Bring base stations closer to the User Equipment (UE)s**

In traditional macro-cell systems, the signal radiated from the base station is subject to large attenuation before reaching the UEs. This is especially critical for indoor UEs where the signal needs to penetrate the walls. High transmit power is needed, which consumes more energy, causes high requirement on the cooling system, and at the same time generates more pollution to the surrounding area [25, 26]. Also, some UEs may not get satisfying QoS due to the weak received signal strength. To overcome this problem, low power base stations can be deployed in most traffic-demanding areas, leading to the heterogeneous network [27–30].

A heterogeneous network is composed of the conventional macro-cell layer and the additionally deployed small-cell layer. The former is used to provide basic coverage over a wide area. Should a macro-cell coverage hole exist, e.g., due to high signal attenuation, small cells can be deployed close to or even inside the macro coverage

hole to guarantee service coverage. Another scenario to benefit from the additional small cells is the traffic hotspot, where local traffic demand can be offloaded to reduce the burden on the macro-layer. Within the small cells, low transmit power is required for the base stations and UEs. It therefore allows reduction of the base station size and also the cost of site renting (Operational Expenditure (OPEX)). Meanwhile, the UE battery life can be significantly prolonged.

As mentioned before, the indoor UEs are expected to generate most of the data volume, while they tend to have much poorer signal strength to the macro-layer than outdoor UEs. Therefore, special attention should be paid to the support of high data rate transmission of indoor UEs, which is also the focus of this thesis. The small base stations to serve the indoor UEs can be of several types, e.g., outdoor micro/pico base stations, relay nodes, or indoor Femto, Distributed Antenna System (DAS), and WiFi systems. They are illustrated in Figure 1.2, and a state of the art on these small cell solutions is provided in the next section.

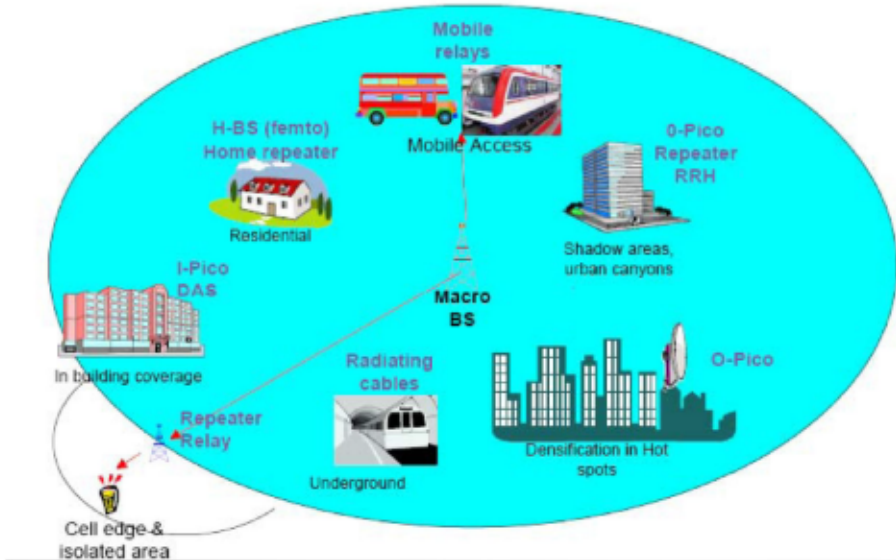


Figure 1.2: A heterogeneous network constituted with the macro-cell and various small cell solutions [31].

## 1.3 Small Cell Solutions for Providing Capacity to Indoor Areas

A conventional cellular system is served by macro base stations, and the coverage area of each macro base station is referred to as a macro-cell. A macro base station is typically tower-mounted and transmits at a high power of tens of Watts. As the wireless data volume increases, the current macro-cell system becomes insufficient to meet this requirement. According to the analysis in the previous sections, the trend for upgrading the most incumbent mobile networks is to switch from 2G/3G network to LTE (making use of MIMO, high modulation and coding scheme etc.), use more spectrum and support the heterogeneous architecture of both macro-cell layer and small cell layer. With the maturity of LTE technology and the availability of new spectrum bands, we discuss in this section several possible small cell solutions for providing better coverage and extra capacity for indoor users. Small cells are those utilizing small-size access points which transmit at low power and cover a relatively small area compared to a conventional outdoor macro site. Such small cell access points include Micro, Pico, Relay, Femto, and WiFi access points. Indoor DAS is also considered a small cell solution because it uses low transmitting power remote antennas, and the coverage area is normally limited by the building area.

### 1.3.1 Outdoor Solutions to Provide Indoor Service (Outside-in)

#### 1. Outdoor Micro/Pico:

Starting from outdoor solutions, the micro/pico base stations can be deployed by the operators in capacity hotspots or macro cell coverage holes [32–34]. The micro/pico base stations are a smaller version of macro base stations, deployed to support a small coverage. Typically the coverage of a micro base station is larger than that of a pico base station. These micro/pico base stations are configured with Open Subscriber Group (OSG) and provide service to nearby UEs [35]. Depending on the relative Reference Signal Received Power (RSRP) measure [36] towards the different network layers, a UE may connect to either of them or even both layers at the same time on different carriers. The latter is known as carrier aggregation in heterogeneous networks and is currently being studied in Third Generation Partnership Project (3GPP) [37]. Due to the fact that the radiating power is much lower from micro/pico cells as compared to the macro cells, only a small fraction of the UEs can be offloaded by the small cells, thus limiting the benefit of the additional cells. A positive bias can be added to the RSRP values of the small cells to overcome this problem. It increases the cell size of the micro/pico cells as UEs farther away from them may still be served,

and is thus referred to as cell Range Extension (RE) [38]. Figure 1.3 shows a macro+micro/pico heterogeneous network, where RE is applied such that more UEs connect to the micro/pico layer.

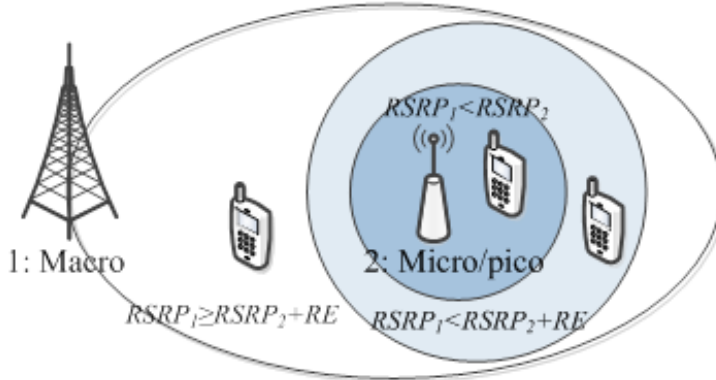


Figure 1.3: A heterogeneous network with range extension in the micro/pico layer.

RE increases the offloading capability at the cost of poorer Signal to Interference plus Noise Ratio (SINR). Should a large RE bias be used (e.g. when macro-layer is heavily loaded and the number of small cells is small), the macro layer will have to be muted on certain time/frequency resources; the small cells can then serve the UEs in the extended range on these resources. Two resource partitioning options have been considered in 3GPP, the frequency domain escape carrier and time domain muting [39, 40]. Deploying micro/pico cells leads to significant gain in energy saving and cost reduction in comparison with macro-cell densification, which has been analyzed in [29, 41–44].

## 2. Relay node:

A Relay Node (RN) is also smaller and lower at transmit power than a macro base station. It connects to the core network, and provides additional links to the UEs. Similar to micro/pico base stations, an RN is typically used as an outdoor solution to improve the macro-cell signal quality. It connects to the core network wirelessly, and thereby avoids the wired backhaul cost for deploying micro/pico base stations. Based on the relay technology being used, an RN can be classified as a layer-1 relay (based on amplify and forward), a layer-2 relay (based on decode-and forward), or layer-3 relay (based on decode-and-forward, but with additional layer-3 processing). In 3GPP the layer-3 relay has been standardized for LTE-Advanced [45]. An RN is an out-band relay if it is deployed on a different carrier from the macro enhanced NodeB (eNB); or an in-band relay if on the same carrier. The out-band relays operate in full-duplex mode. They can transmit to UEs and receive from the eNB simultaneously. On the other hand, the in-band relays may have to

follow the half-duplex mode unless enough spatial separation, filtering or enhanced interference cancellation is available [30]. The additional bandwidth requirement of out-band relay and the half-duplexing mode of the in-band relay make the access link unable to use all the available radio resources, and therefore impose limitations on the gain of relaying. The performance of relaying has been evaluated in [46,47], and the cost comparison between other small cell solutions, e.g. micro/pico systems, is made in [48–53].

Depending on their visibility to the user equipment (UE), an RN also falls in one of the following types: a type-1 relay (non-transparent relay in Worldwide Interoperability for Microwave Access (WiMAX)) or a type-2 relay (transparent) [54–56]. A network with conventional macro base stations and the two types of relays is illustrated in Figure 1.4. A type 1 relay is non-transparent to the UE. It has its own physical identity and transmits the common reference signal and the control information for the eNB. It appears as a regular eNB to all the UEs, and the main objective is to extend macro cell coverage. A type 2 relay does not have its own physical identity and is transparent to the UE. As can be seen from Figure 1.4, while a UE maintains the connection to the macro base station, it is offered additional access links via a type 2 relay. Therefore, the multipath diversity is increased. Meanwhile, the signal strength from/to the UEs will also be increased due to the additional links. Overall, higher system capacity can be achieved from the deployment of type 2 relays.

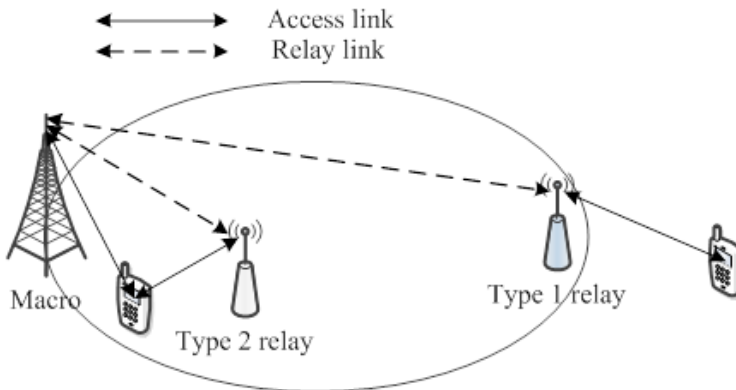


Figure 1.4: A network with different types of relay nodes.

These above-mentioned outdoor solutions are able to fill the macro cell coverage hole so as to guarantee ubiquitous wireless connectivity. They are also able to increase the system capacity. However, the capacity gain is normally insufficient to fulfill the high capacity demand for indoor users. One of the reasons is the high wall penetration loss: when base stations are placed outdoor, the indoor

users that require high capacity actually get a poorer signal quality compared to outdoor users with lower capacity demand. Another reason lies in the fact that these outdoor systems are sparsely deployed within the macro cell area. This increases the spatial frequency reuse factor, but not to the extent that can meet the high traffic demand for indoor hotspot areas. In such places, a densely deployed small cell layer with even lower transmit power is preferable.

### 1.3.2 Dedicated Indoor Solutions

Dedicated small cell systems can be deployed indoor to avoid the high penetration loss through the external walls [57, 58]. While achieving good signal quality, the indoor deployment also exploits the benefit of the wall penetration loss. It makes the indoor system less vulnerable to macro interference, and reduces the outgoing interference to the macro as well. In the following, we give an overview of the different indoor solutions. A detailed description of the ones considered in this thesis will be provided in the next chapter.

1. Indoor DAS:

A DAS is composed of several spatially distributed antenna elements that connect to a common source. It is normally installed as a single cell solution and extends the macro site capacity indoor [59, 60]. The single-cell principle limits the capacity gain that DAS can achieve. However, it can also be sectorized into multiple cells for higher capacity. The performance of the indoor DAS system has been evaluated in [61–64]. The improvement of signal quality using DAS has been proved by theoretical analysis, simulation studies and field measurement through [65–73]. The authors of [74–76] compared the performance of DAS with the outdoor-to-indoor solutions or more typically to a single indoor Pico base station solution [74–76], which all indicate superior performance or user experience of indoor DAS to other solutions under comparison.

2. Indoor Femto System:

A Femto Access Point (FAP) is essentially a condensed version of a macro base station, with all the basic functionalities. Femtocells are supported in both WiMAX and LTE standards [77–80]. In 3GPP, a FAP is referred to as a Home enhanced NodeB (HeNB). FAPs are low-transmit-power base stations typically deployed indoors in residential, enterprise, and hotspot areas. They operate on licensed spectrum and provide data service to subscribers by connecting them to operator's core network with the help of wired backhaul. The deployment of multiple femtocells within a geographically limited area achieves high spatial frequency reuse, and hence offers significant capacity gain [81].

It is worth noting that the pico base stations are also suitable for indoor usage. They can be mounted on the walls or ceilings, thus avoiding the expense of site renting. An indoor pico and femto cell operates in a similar manner. However, a pico base station has higher transmit power than a FAP, and hence serves a larger area. It is intended for enterprise usage only, whereas a FAP is applicable for both personal and business usage.

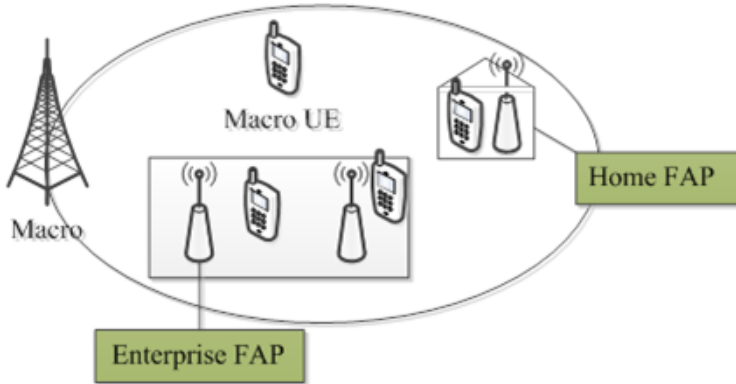


Figure 1.5: A heterogeneous network with macro base station, enterprise and home FAPs.

### 3. Indoor WiFi System:

WiFi is a mature technology already in use for many years. The term “WiFi” refers to all products that use the Institute of Electrical and Electronics Engineers (IEEE) 802.11 family of standards, e.g., 802.11a/b/g/n [82, 83]. WiFi also offers the possibility of offloading the traffic similar to the Femtocells [84–86]. However, the fundamental difference to a femtocell is that WiFi operates on the unlicensed band, which has both pros and cons. The benefit is that it makes use of additional bandwidth, which comes at no cost to the macro cell system. Also, WiFi is supported in a variety of products including computers, laptops, tablets and smartphones etc. Some general concerns about WiFi include the security issue as well as the performance reliability [87]. In [88], several security challenges in WiFi have been discussed, including the vulnerabilities to interception, injection, jamming etc. The Medium Access Control (MAC) layer of WiFi uses the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol [89, 90], which may cause low resource utilization when many UEs exist [91]. Other than low resource utilization, collision may still happen due to the “hidden node” effect, where two UEs do not see each other and may decide to transmit at the same time [92, 93]. The CSMA/CA is also sensitive to the imperfect sensing [94]. Some experimental studies also indicate that the QoS for multimedia services, e.g. VoIP in WiFi system, is difficult to guarantee [95, 96].

Despite some efforts being spent on improving the WiFi performance [97–102], e.g. by resolving the hidden node problem or improving the MAC layer design, it is not as good as the legacy mobile base stations which are designed to optimize mobile user experience. Although the wide availability of WiFi-capable devices and the ease of installation of WiFi access points make WiFi an attractive solution to services that are less sensitive to security and quality, it is not the most appropriate solution for corporate usage as high voice service performance is expected.

## 1.4 Motivation of the Study

As already shown in Figure 1.1, most of the wireless data traffic is (and will be) generated from inside the building. It is thus beneficial to bring the Base Station (BS)s closer to the UEs, so as to overcome the distance related attenuation. Furthermore, in scenarios where the capacity demand is high, and the large wall penetration loss prevents the outdoor BSs from offering satisfying signal quality, it may be advantageous to even bring the BSs inside the building. Based on these considerations, we set our focus on the dedicated in-building solutions. We select the DAS and femtocell system as the suitable solution to address future indoor capacity shortage problem.

As Femto products have led their way successfully into the market in the past couple of years, variant debates have arisen on the internet and in international telecommunication workshops whether Femto will be the technology that will ultimately replace DAS. While supporters of each side address their points of view in a very confident and convincing tongue, their conclusion seems to be derived from distinctive perspectives. Supporters of DAS believe that DAS still takes advantage of the large coverage and chunk efficiency of 3G service. Meanwhile, using small-range Femtocells to cover the same area will result in installing a huge number of Femto access points in the same facility. They are worried that this will involve great planning and implementation effort and create a higher amount of cash investment. Supporters of Femto technology argue that due to the low cost of Femto access point and its easy-to-deploy plug-and-play feature, Femto may turn out to be the more economical solution. Besides, due to denser spatial reuse of the scarce spectrum resource, a multi-Femto deployment will bring about multiple folds of capacity increase. The argument of both sides seems reasonable and compelling, but rarely has anyone shown any practical data to support his/her statement. Behind these heated debates online and in real life, there are surprisingly few dedicated studies to evaluate and quantify the efficiency of the deployment of both solutions in a unified view considering both performance and cost.

Performance-wise, seldom work has compared the two systems for indoor applica-



tions in detailed categorized scenarios according to service type and traffic demand in-building. Cost-wise, the cost analysis is seldom done in combination with performance, and it is even rarer to see a numerical evaluation of the economical comparison of the two systems.

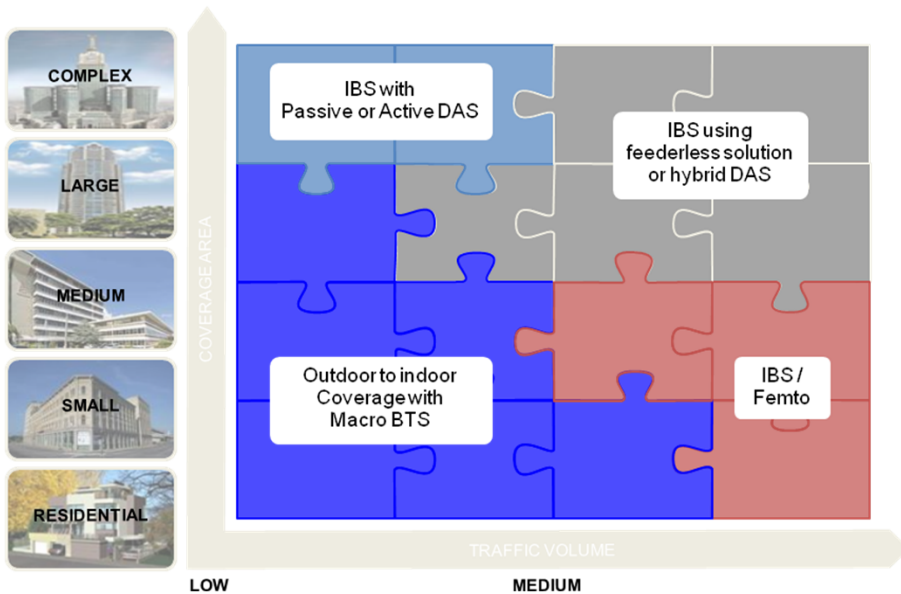


Figure 1.6: Choosing the appropriate indoor technology depending on the deployment scenario<sup>3</sup>.

Pictures such as Figure 1.6 have made their appearance in many reports and tutorials to depict the division of application of Femto and DAS under different circumstances. Although the information conveyed by the figure is widely recognized as the rule-of-thumb deployment strategy, the details depicted here are vague, from how to define the categories of building size to what capacity each system could provide. In looking forward to the evolution of indoor mobile networks, we may want to know whether this conclusion will still be true under variant conditions: Will the conclusion change if the in-building traffic demand varies, for example providing future very high data rate services? What will the situation be if the enterprise Femto price is much lower or higher than predicted and used as assumptions when generating the figure shown above? Are there other factors that will affect the result, like the type of building or the existing indoor network constructions? How sensitive is the result to local environments from different regions of the world such as regulations, sales market, labor cost, the trend of availability of mobile backhaul, etc.

<sup>3</sup>From NSN internal report. IBS: in-building solution; BTS: base transceiver station.

There have been numerous studies<sup>4</sup> concerning Heterogeneous Network (HetNet) interference and mobility management, throughput and outage performance, cost analysis, and business case studies. However, these are mostly separate works. We try to put together the performance and cost studies as they should inherently interact and leverage between each other. Moreover, most of the studies assume deployment cases for residential home or apartment buildings, focused on HetNet feature. There are few studies about Enterprise solutions. As shown in Figure 1.1, the traffic generated from enterprise premises also accounts for a large portion of the total volume, and hence attention should be paid to this as well. All these aspects motivate this PhD study.

## 1.5 Problem Delineation

Within the scope of this PhD study, we focus on the dedicated in-building systems in enterprise scenarios. Among the listed indoor solutions, effort is devoted to the DAS and femtocell systems. The problems that will be addressed in this study are listed below:

1. What is the benefit of deploying the DAS and femtocell system in an enterprise building?

The baseline performance of DAS and femtocell system will be obtained and compared to each other in an enterprise building. The benefit of having a different number of distributed antenna elements (for DAS) and a different number of femtocells will be shown.

2. How to further improve the indoor system performance?

The indoor system is significantly different from the conventional macro-cell system, and hence requires dedicated optimization solutions to best exploit its benefit. Enhancement in packet scheduler will be developed to coordinate the transmission among neighboring antenna elements / femtocells. Furthermore, the placement of antennas and the resource sharing between femtocells will also be addressed.

3. What is the impact of cell load on system performance?

While most of the existing studies on indoor system are based on the assumption of full load situation, the interference condition may be quite different with a realistic traffic model and fractional load across cells. The impact of cell load on the indoor system performance will be analyzed, and the guideline for optimizing the performance based on cell load will be obtained.

4. How much is the cost of different indoor systems?

For the commercialization of an indoor system, it is necessary to know its

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<sup>4</sup>Examples and state of the art research results will be presented in Chapter 2.

associated cost. The cost may come from different sources, e.g. the Capital Expenditure (CAPEX) that includes the equipment and installation cost, as well as the OPEX including the cost to keep the system running and perform the necessary maintenance. A cost model will be developed for estimation of the total cost of different indoor systems.

5. What is the most economical upgrading path for current systems to satisfy the growing traffic demand?

Using the previously obtained system performance and the cost model, it is possible to estimate the additional cost for upgrading the current system to meet the predicted traffic growth. The most economical upgrading path for an enterprise building will be identified.

## 1.6 Research Methodology

This study makes an extensive examination based on these two systems for network evolution towards the LTE to achieve a techno-economical evaluation of high capacity indoor wireless solutions. As discussed in previous sections, the two important issues when complementing the macro cells with small cells are performance and cost. Naturally, we divide the study of this thesis into these two major aspects accordingly: radio performance evaluation and financial economical comparison. Firstly, their radio performance for indoor high-data-rate deployment is evaluated in the LTE downlink context. Possible system enhancement is proposed to improve the system performance. Then the system cost analysis is conducted and compared between systems in distinctive applications.

The performance is obtained via system level simulation. For this purpose, a Matlab based simulator was developed. It models a multi-floor enterprise building located within a macro network, and hence also receives signal/interference from outdoor macro sites. Multiple users exist in the system, and the basic radio resource management features e.g. adaptive modulation and coding, Hybrid Automatic Repeat Request (HARQ) and packet scheduling are explicitly modeled. As to the propagation statistics, both path loss and shadowing are considered. To generalize the findings, we consider two types of building model: the general indoor office model from WINNER II [103], and a site-specific case with real path loss measurement [104]. Fast fading is not modeled. Link level is abstracted by mapping the SINR to throughput using the modified Shannon formula which is calibrated based on LTE physical layer performance [105]. The gain of MIMO transmission is captured by further modification of the SINR to throughput mapping formula.

In the first half of the thesis, we first focus on the performance comparison between Femto and DAS using the developed simulation tool, trying to answer the

first question in Section 1.5. Afterwards, the possibility of further improving the performance will be analyzed, and new methods will be developed for this purpose. The impact of cell load on system performance will also be analyzed by using a finite buffer traffic model with Poisson arrival. The aim of this study is to obtain the system capacity limit of the different technologies. Later, this capacity limit is used to determine the number of FAP/DAS to be deployed, based on the traffic need.

In the second half of this PhD study, the cost characteristics for the two chosen solutions are analyzed. Separate cost models will firstly be developed for the considered indoor solutions. We then make use of the system capacity obtained before, and numerically calculate the total cost of ownership (TCO) for each of them using the cost model. The aim of this study is to find the appropriate path for installing an indoor system or upgrading an existing one, which may vary depending on the building size, structure, the traffic requirement as well as the equipment/labor cost.

## 1.7 Thesis Outline

The two dedicated indoor solutions based on DAS and Femto are introduced in detail in Chapter 2. The state-of-the-art researches are provided on topics related to their indoor applications and performance. The centralized scheduling system is briefly introduced in the last part of the chapter. The performance of these systems is investigated and compared in an office environment in Chapter 3 and Chapter 4.

Chapter 3 considers a fully loaded network, where the multi-Femto system performance is largely deteriorated due to heavy inter-cell interference. A Quality-Guaranteed (QG) scheduler is developed to improve the cell edge user experience. Other possibilities of e.g. frequency reuse and cell-level coordination are also studied to further improve the capacity and a centralized coordination scheme is proposed. The contributions in this chapter are published in the following conference and magazine papers:

- Zhen Liu, Troels Sørensen, Jeroen Wigard, Jolma Petri, Troels Kolding, and Preben Mogensen, “A Site-Specific Study of In-Building Wireless Solutions,” *in Proc. IEEE VTC*, May, 2010.
- Zhen Liu, Troels Sørensen, Jeroen Wigard, and Preben Mogensen, “DAS, Uncoordinated Femto and Joint Scheduling Systems for In-building Wireless Solutions,” *in Proc. IEEE VTC*, May, 2011.
- Zhen Liu, Troels Sørensen, Jeroen Wigard, Jolma Petri, Troels Kolding, and

Preben Mogensen, “Soluções para aumentar a cobertura celular dentro de edifícios,” *RTI magazine (invited paper)*, May, 2011.

Chapter 4 examines the previously developed algorithms in a partially loaded network, which is usually the case during non-busy hours. In this situation, the multi-Femto system demonstrates much higher capacity compared to the DAS. The finds contribute to a conference paper:

- Zhen Liu, Troels Sørensen, and Preben Mogensen, “Site-specific Study of In-building Wireless Solutions with Poisson Traffic,” in *Proc. IEEE VTC*, Sep, 2011.

In Chapter 5, we investigate the financial economic analysis for indoor DAS and Femto systems based on the TCO analysis. Combined with the system performance evaluation in previous chapters, the TCO analysis will help us obtain a better understanding of the future cost-efficient indoor solutions depending on different application scenarios. The following paper summarizes the main finding of this chapter:

- Zhen Liu, Troels Kolding, Preben Mogensen, Benny Vejgaard, and Troels Sørensen, “Economical Comparison of Enterprise In-building Wireless Solutions using DAS and Femto,” in *Proc. IEEE VTC*, Sep, 2012.

Finally, the conclusions are drawn in Chapter 6, and a summary of the overall study is provided therein.

# Overview of Studied Indoor Wireless Systems

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In this chapter we focus on the two selected dedicated indoor wireless solutions, DAS and Femtocells. We introduce in detail the concept and system design of each system in the enterprise in-building applications. Their advantages and disadvantages for indoor usage are discussed, which is followed by an introduction of the state-of-the-art research of each system. At last, their respective downlink radio transmission is presented in mathematical format. A centralized scheduling system employing interference avoidance techniques is proposed afterwards. The proposed system is designed in order to compensate for the defects of DAS and multi-cell Femto system and boost simultaneously the average and outage user throughput.

## 2.1 Distributed Antenna System

Like Femto has the Femto Forum<sup>1</sup>, the distributed antenna system also has its regulation organization counterpart, called the DAS Forum ([www.thedasforum.org](http://www.thedasforum.org)). By the definition of the DAS Forum, a distributed antenna system is “a network of spatially separated antenna nodes connected to a common source via transport medium that provides wireless service within a geographic area or structure”.

The idea of the distributed antenna system is to divide the big coverage area into multiple small coverage areas which are covered by localized distributed antenna elements, illustrated in Figure 2.1. The transmitted power is split into several antenna elements, distributed in space. Early studies in [58, 106–109] show that by adopting distributed antennas reduced total power and improved reliability can be achieved compared to a centrally located single antenna system.

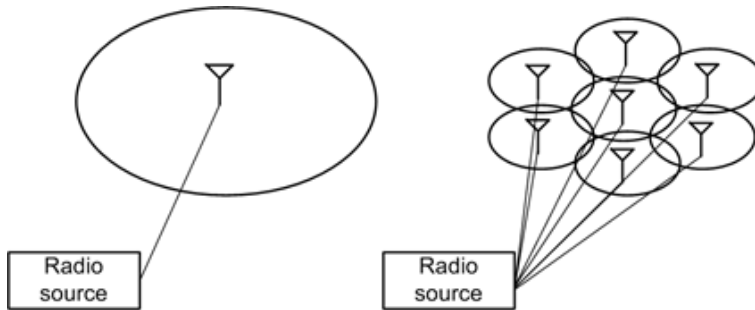


Figure 2.1: Comparison of configurations of single and distributed antenna system.

In DAS, the radio signal from the same sector of a Base Transceiver Station (BTS) is broadcast to multiple antennas at the same time. The term simulcast is used to describe this operation. By simulcast, multiple copies of the same signal are radiated from the antennas, mixed in the wireless channel and combined at the front end of the mobile receiver. Simulcast was first used in Cable TV (CATV) networks [110]. Its effectiveness in improving Signal to Noise Ratio (SNR) performance, lowering transmission power, reducing handovers and increasing overall system performance is proven by both measurements [106–108] and theoretical studies [109, 111]. The authors in [58] show that by using a group of  $N$  low-power antennas to cover the same area, the overall radiated power is reduced by approximately a factor of  $N^{\alpha/2-1}$  where simple power law path loss model with path loss exponent  $\alpha$  is assumed. Otherwise, with the same total transmit power, the coverage area can be extended by  $N^{\alpha/2-1}$  times that of the single antenna system. The in-building deployment of DAS was first introduced by A. M. Saleh et al. [57] in 1987. Figure 2.2 shows an application example of DAS installed in an office building. The distributed antenna systems can be deployed indoor to avoid the high penetration loss through the external walls which is an effective means to extend the coverage of outdoor network. When installed indoors, the distributed architecture has also great advantages in shortening the distance of the wireless path between transmitter and receiver antennas and in combating severe shadowing effect caused by inner walls, structures and furniture. The indoor signal-to-noise ratio is expected to be much improved by the usage of DAS.

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<sup>1</sup>Now Small Cell Forum.



Figure 2.2: An example of the DAS deployed indoor.

### 2.1.1 Different Types of DAS

In general, there are two types of distributed antenna systems depending on the composition of passive/active devices in the distributed system [111].

#### Passive DAS

The DAS is a passive DAS if the distributed system consists of purely passive components, such as cables, combiners, power splitters, directional couplers, etc. The block diagram of a typical in-building passive DAS is illustrated in Figure 2.3. Detailed introduction of variant passive components used in passive DAS can be found in [111].

The passive DAS does not convert the Radio Frequency (RF) signal (i.e., demodulation/re-modulation, up/down-conversion, etc.) or boost the RF signal power to compensate for the cable loss in the distributed system. The signal power experiences partitioning and loss when the signal travels through the passive distributed system. In the downlink, the attenuated signal is finally output by the remote antennas; in the uplink, multiple copies of the uplink signal collected from all remote antennas



are sent back to the base station and get attenuated in the cable.

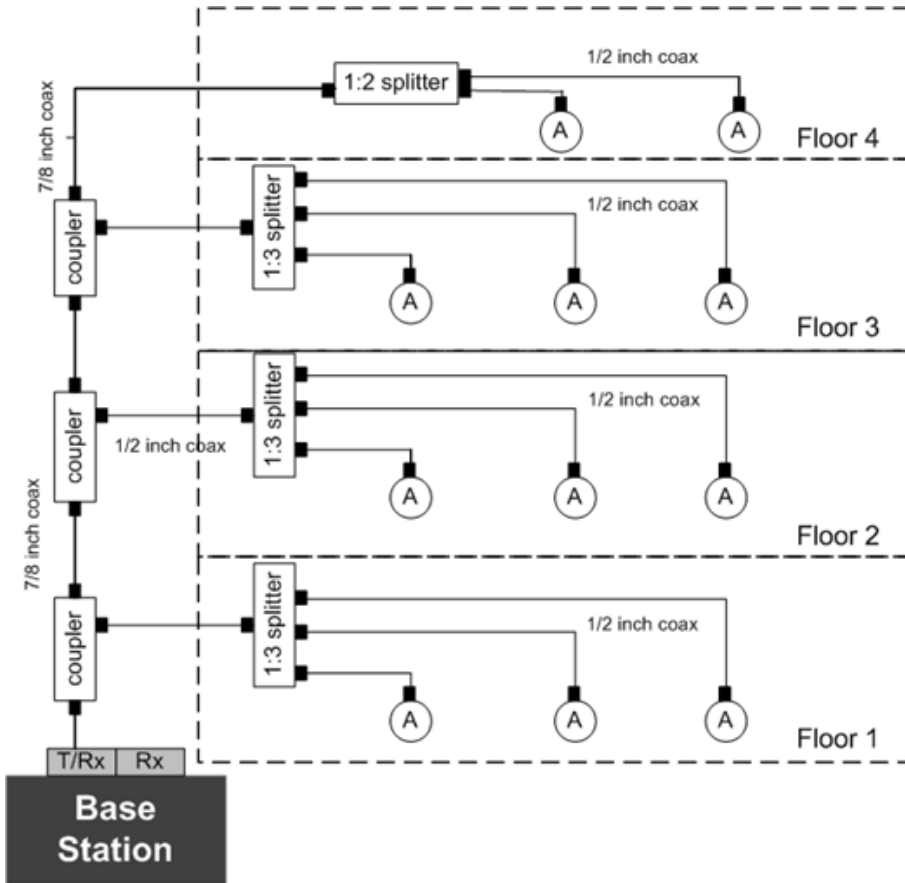


Figure 2.3: Block diagram of a typical passive DAS.

### Active DAS

The second type of DAS is called the active DAS. The active DAS hints by its name that its distributed system contains active components. An active component used for the active DAS can be power amplifier, signal converter, etc. The most commonly seen active DAS is the active fiber DAS. The block diagram of a typical in-building active fiber DAS is illustrated in Figure 2.4. The fiber DAS transforms the RF signal to optical analog or digital signal that can be transmitted over fiber links. The RF signal is then regenerated and possibly amplified at the optical remote unit [111]. If the regenerated RF signal is sent directly to one antenna, it is a pure active DAS. However, normally the RF signal is divided and further distributed by coaxial cable. This kind of active DAS is also called hybrid DAS.

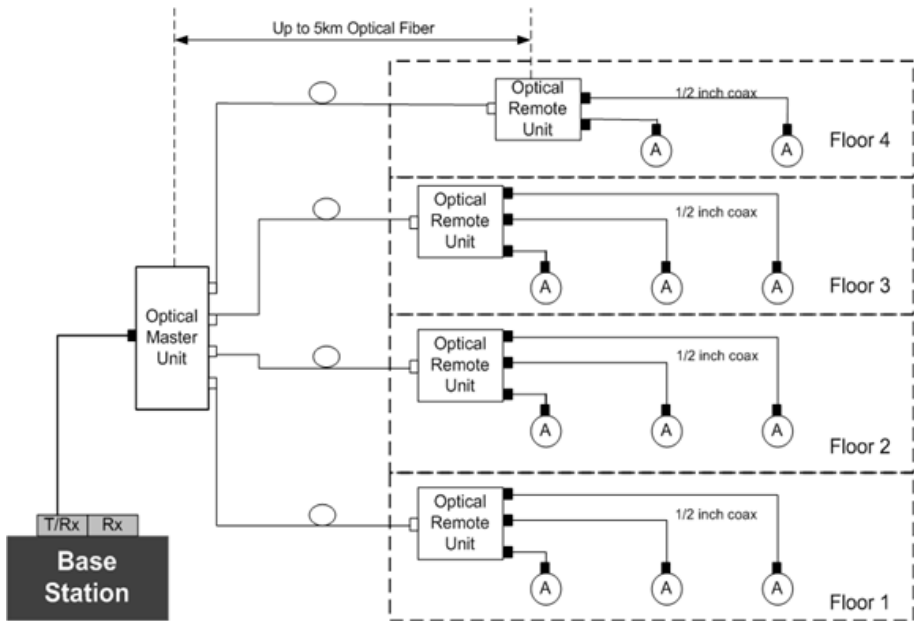


Figure 2.4: Block diagram of a typical active Fiber DAS.

By converting the RF signal to optical signal and recovering at the remote unit, the RF signal can be transported from the base station to the output of the remote unit loss free avoiding the high cable loss as in the passive DAS. The distance of the fiber connection can extend up to several kilometers. This makes the active DAS more suitable than the passive DAS for distributing signal to long distance fields or in very large areas, where the target coverage area is very far from the base station location.

Normally, the optical master unit and remote unit are costly. Rather than converting the RF signal into optical signal and recovering it back at the antenna side, why not use fiber to deliver the baseband signal directly to the remote field and up-convert it to the carrier frequency? The idea of separating the base station into two parts and connect them by fiber optic makes an alternative cheaper way to construct a hybrid fiber DAS possible. The block diagram of such a system can be seen in Figure 2.5. The mobile network equipment vendors divide the conventional integrated single base station box into two parts: the Baseband Module/Unit (BBU) and the Remote Radio Unit (RRU) or Remote Radio Head (RRH)<sup>2</sup> [112]. The BBU and RRUs/RRHs are connected by fiber links through Open Base Station Architecture Initiative (OBSAI) interface, so that the remote radio module can be installed near the targeted coverage area. The remote radio module is produced light weighted so that it can easily be mounted on walls or hidden behind

construction structures, in case no dedicated equipment room is available.

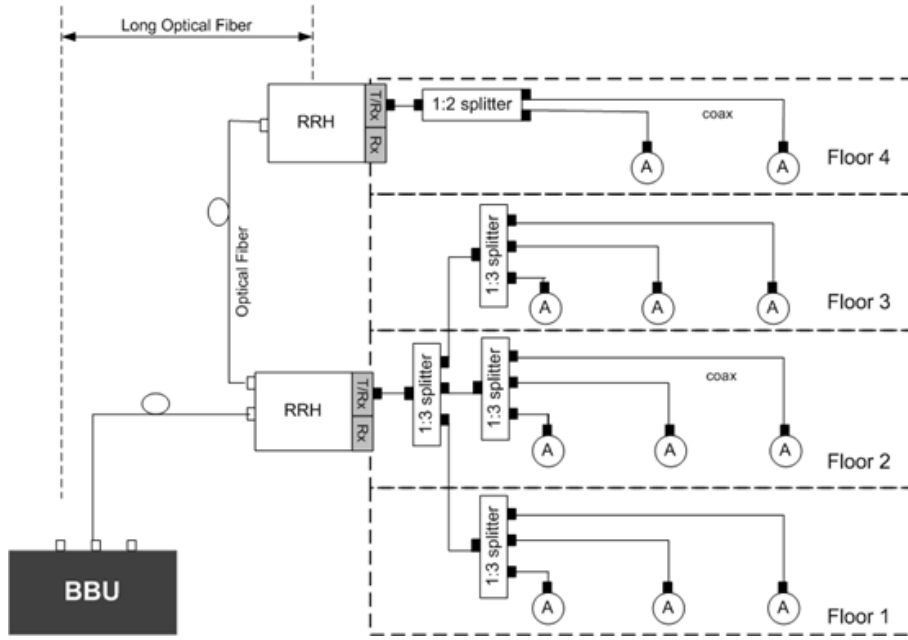


Figure 2.5: Block diagram of a BBU+RRU DAS.

The vast majority of indoor DAS installed in the past years are single-antenna systems. The single-antenna system means that the base station is configured as single transmitter in downlink, and at the remote antenna side there is a single antenna at each cluster, as illustrated in Figure 2.6. The downlink transmission is a Single Input Single Output (SISO) or Single Input Multiple Output (SIMO) system depending on the number of receiving antennas on the mobile device. The single-input is determined by the configuration of the base station, that a maximum of one signal stream is transmitted, which is independent of the number of distributed remote antennas. We call this type of DAS the single-antenna DAS or SISO/SIMO DAS for short.

However, the increasing mobile data usage in recent years and the maturity of MIMO techniques in HSPA and LTE systems have accelerated the need for MIMO DAS to boost capacity and peak data rate in indoor hot spots. Figure 2.7 illustrates how a two-by-two MIMO DAS works in the indoor environment. The key to good MIMO performance is a thorough separation of the signal transport from the base station to the remote antenna output. So any DAS containing a passive distributed part has to install two parallel passive distributed systems [111].

<sup>2</sup>RRU and RRH differentiate in terms of capacity.

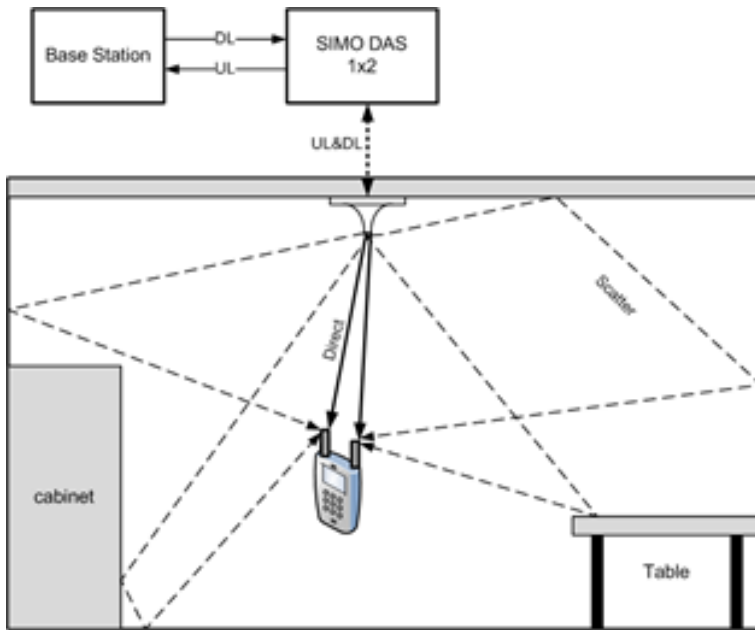


Figure 2.6: Illustration of an indoor DAS with 1-by-2 input-output (SIMO) configuration.

More discussions and illustrations of engineering the MIMO DAS are available in Chapter 5.

### 2.1.2 DAS Related Study

Early studies on DAS focus on the improved signal quality and field measurement of indoor channel property [65–73]. Mostly because at that time the indoor DAS was majorly used to fill the indoor coverage holes or deployed as legacy systems required for specific buildings. It was not considered as capacity boosters replacing traditional outdoor base stations. In [76], the performance of indoor DAS is compared with outdoor macro, and in [74, 75], with indoor Pico. In both studies DAS demonstrates advantage in improved signal quality by overcoming outer wall penetration loss and shadowing effect. Similar studies and results can also be found in [74–76].

Later studies start to look at ways to improve or optimize the DAS performance

<sup>4</sup>This illustration is a reproduction of Figure 2.53 in the book of “Indoor radio planning: a practical guide for GSM, Digital Cellular Service (DCS), Universal Mobile Telecommunications System (UMTS), HSPA and LTE” [111].

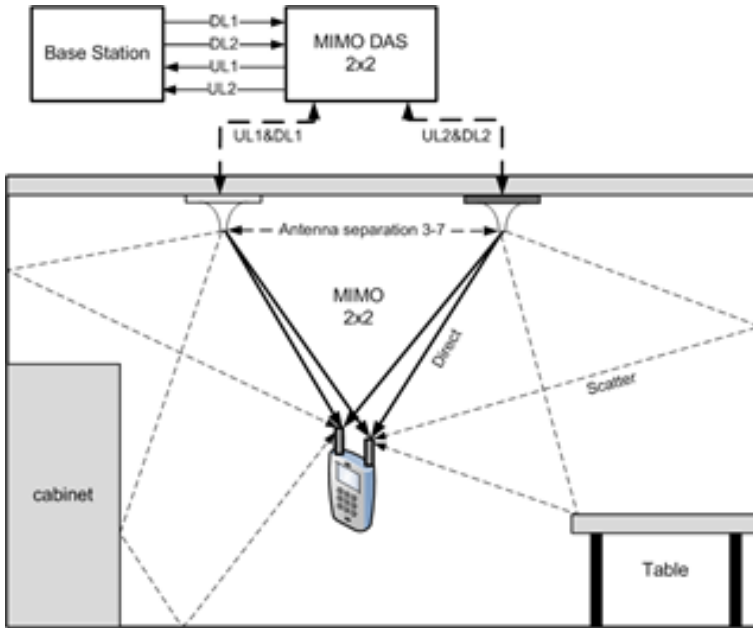


Figure 2.7: Illustration of an indoor DAS with 2-by-2 input-output (MIMO) configuration<sup>4</sup>.

by means of location optimization, MIMO, intelligent frequency reuse and coordinated scheduling, etc. The good performance of DAS relies on an adequate number of distributed remote antennas and their optimized placement, which should be planned for each specific building [61, 62]. However, in [63] and [64] the authors have found that with sufficient high number of antennas, the requirement on Access Point (AP) placement can be relaxed. They proved that with a sufficient number of antennas, even random placement of distributed antennas can achieve the performance as good as a system with coordinated placement of antennas.

The application of MIMO techniques has also been investigated in the distributed antenna system. In the study of [113], the authors prove through indoor channel measurement that MIMO can improve the system performance significantly even under LOS propagation conditions. A feasibility study of MIMO DAS from hardware and engineering perspective is conducted in [114]. Other types of MIMO applications such as utilizing distributed antennas to achieve distributed MIMO is studied in [115]. Transmit macro-diversity is studied in [107–109]. In [107] and [109], co-phase transmission is recommended for maximizing the downlink SINR under per antenna power constraints. When the power constraint does not exist, the best transmission strategy of DAS is transmit Maximal Ratio Combining (MRC) [116].

The DAS is normally installed as a single cell solution for the macro-cell coverage problem [59, 60]. However, it can also be sectorized into multiple cells to achieve high capacity. The authors from [63, 67, 68, 117] investigate proper approaches to improve the multi-cell DAS capacity and efficient means to minimize the inter-cell interference. In [67] and [68], the authors suggest the use of selective transmission instead of simulcast in terms of achievable ergodic capacity. With selective transmission, only the antenna with the best channel transmits to the user, other antennas belonging to the same cell keep “silent” during the transmission which largely brings down the inter-cell interference to neighboring cells. Both selective transmission and macro diversity achieved by means of phase steering are mature mechanisms with low complexity, but they are hard to realize under the current 3GPP standardization framework on mobile user equipment measurement capacity: these mechanisms require not only individual remote antennas to be identifiable at both base station and user equipment, but also require the user to give feedback on the accurate and instant channel measurements related to each individual remote antenna. Such measurement and feedback is not supported by the current release of the 3GPP standard.

The study in [67] suggests the use of denser frequency reuse by means of even smaller cell sizes to achieve high capacity. The idea of intelligent channel reuse within the building is also recommended in [118] and performance evaluated in [117]. If the frequency resource can be reused among different antennas to serve different users, then the coverage of each remote antenna effectively forms an individual cell. The coordination between multiple cells is not a new concept which has been studied for years under the topic of Coordinated Multi-Point (CoMP). Previously, the CoMP concept was seldom viewed as within the scope of DAS. In 2011, on the Globecom DAS workshop<sup>5</sup>, an extended definition of DAS was brought up in the panel [119, 120], in which the distributed antenna elements are no longer connected to a common radio source, but to the radio source of their individual cell/sector. With an architecture like a distributed antenna system, coordination between antenna elements can be conducted jointly at the central BS location. More similar researches can be found in [118, 121–123], introducing variant coordination mechanisms for this type of “enhanced DAS”.

As to the cost analysis for indoor DAS, only a few studies exist [61, 124]. To the best knowledge of the author, none of the studies have provided a numerical calculation and comparison of cost of the different indoor systems, especially for variant buildings and service types. In [125], the DAS is, for the first time, taken as an alternative solution in a network cost analysis to be compared with Femto, WiFi based small cell solutions. However, as the analysis is for the whole network upgrade, the cost of the DAS lacks details, unaltered by the building specific characteristics.

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<sup>5</sup>[http://das-workshop.upatras.gr/IEEE\\_First\\_workshop\\_on\\_DAS\\_for\\_broadband\\_mobile\\_systems/Main\\_page.html](http://das-workshop.upatras.gr/IEEE_First_workshop_on_DAS_for_broadband_mobile_systems/Main_page.html)

## 2.2 Femto

An FAP is essentially a condensed version of a macro base station, with all the basic functionalities. Femtocells are supported in both WiMAX and 3GPP standards [77–80]. In 3GPP, an LTE FAP is referred to as a Home enhanced NodeB (HeNB). Our study is based on LTE FAPs, therefore the terms of ‘FAP’ and ‘HeNB’ are used interchangeably within the scope of this PhD thesis.

FAPs are low-transmit-power base stations typically deployed indoors in residential, enterprise, and hotspot areas. They operate on licensed spectrum and provide data service to subscribers by connecting them to the operator’s core network with the help of existing broadband connectivity. In most circumstances, wired backhaul is employed. However, the possibility of using wireless backhaul for small cells is also under investigation [105].

Other than Femto, there are other small cell solutions, e.g. the pico and micro base stations. The most distinguishable difference between these solutions is their coverage area and transmit power: a typical FAP transmits at maximum 200 mW and covers tens of meters of range; a pico base station can cover up to two hundred meters with 4 W power; with even higher power, a micro base station can offer service within around 1 km range in outdoor environment. These solutions are used for different purposes: the micro base station is usually deployed to provide coverage, similar to a traditional macro base station. On the other hand, the pico base station and FAP are mostly deployed to achieve high data rate in hotspot areas. From a functionality point of view, the Femto/pico/micro solutions are quite similar, as they have to serve as a normal base station and favor the self-organized mode to minimize the need for network planning. Moreover, they all need to deal with inter-layer interference if co-channel deployed with macro-cells. Therefore, an algorithm developed for one of them can easily be transplanted to others with very few or no changes to achieve the same purpose. In this PhD thesis, several interference coordination algorithms will be developed and evaluated in the Femto system. As such, they are also applicable to pico/micro systems.

### 2.2.1 Standardization of LTE HeNB

The support for LTE HeNBs has been standardized in 3GPP. The function, interface and system architecture for supporting HeNB is described in [118]; the radio frequency requirements for HeNB are detailed in [79] and [126] for Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) systems, respectively. A short summary is presented here.

### 2.2.1.1 Architecture

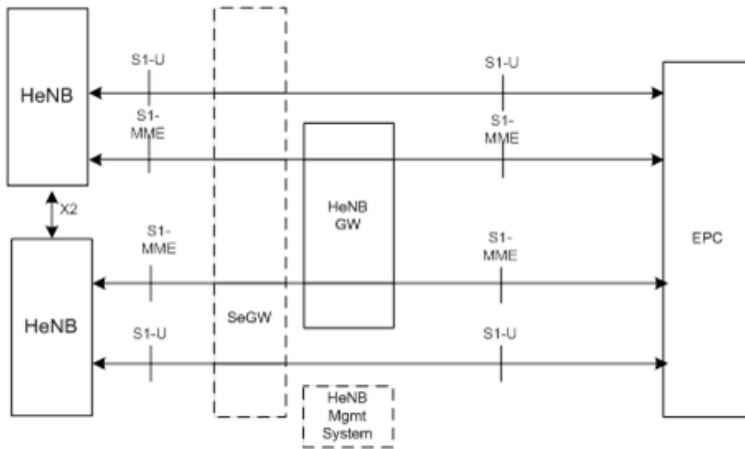


Figure 2.8: LTE HeNB Logical Architecture [118].

Figure 2.8 illustrates the logical architecture of an LTE FAP, from which it can be seen that an FAP can directly connect to the Evolved Packet Core (EPC) and Mobility Management Entity (MME) via the S1 interface, or through the Femto gateway (HeNB Gate Way (GW)). The HeNB GW can concentrate a large number of HeNBs. It appears to the MME as an eNB, and appears to the HeNB as an MME. The S1 interface between the HeNB and the EPC is the same, no matter whether the HeNB is connected to the EPC via a HeNB GW or not [118].

The HeNBs can also connect to each other with the X2 interface [127]. X2 is a point-to-point interface between two LTE eNBs which supports the exchange of signaling information. The X2-connected eNBs are not necessarily supplied by the same manufacturer [19]. Again, the availability of an X2 connection is independent of whether the HeNBs connect to the HeNB GW or directly to EPC. The overall LTE network architecture with deployed HeNB GW is shown in Figure 2.9. It is worth noting that the S5 interface is only required by HeNBs supporting Local IP Access (LIPA) function [26], which will be discussed later. For detailed description of the interfaces (e.g. S1, S5), please refer to [128].

### 2.2.1.2 Access Control and QoS Requirements

The FAPs normally operate under the Closed Subscriber Group (CSG) mode and provide service to a dedicated group of people. However, subject to operator and FAP Hosting Party agreement, the operator shall be able to configure the FAPs with open, hybrid or closed access mode [26]:



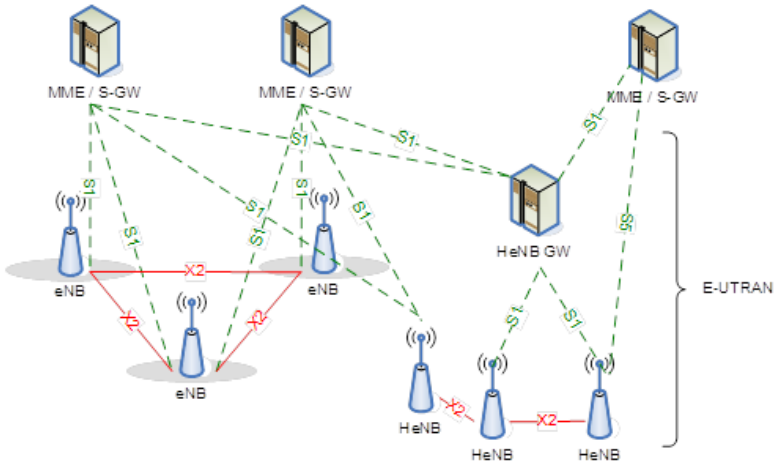


Figure 2.9: Overall LTE Network Architecture with deployed HeNB GW [118].

- When the FAP is configured for closed access mode, only users that belong to its associated CSG shall be able to obtain services.
- When the FAP is configured for open access mode, it shall be possible for the FAP to provide services to subscribers of any Public Land Mobile Network (PLMN), subject to roaming agreement.
- When the FAP is configured for hybrid access mode, it shall be possible for the FAP to provide services to:
  - its associated CSG members, and
  - subscribers of any PLMN not belonging to its associated CSG, subject to roaming agreement.

For the hybrid case where the FAP provides service to both CSG and non-CSG UEs, different QoS targets may be implied to different UE groups. For this purpose, the MME shall inform the FAP whether a newly accessed UE is within the CSG list or not. Based on the CSG membership, the offered QoS for UEs served by this Hybrid Cell may be modified as follows [118]:

- The FAP may distinguish between a CSG member and non-member when determining whether to hand over a UE, which Guaranteed Bit Rate (GBR) bearers to admit and which GBR bearers to deactivate;
- The FAP may distinguish between a CSG member and non-member for handover and packet scheduling on Uu interface (including reduced QoS) of non-GBR bearers.

### 2.2.1.3 FAP Functional Requirements

According to the 3GPP specification [118], an LTE FAP should support the same functions as a conventional macro eNB, which are listed as follows:

- Functions for Radio Resource Management (RRM): Radio Bearer Control, Radio Admission Control, Connection Mobility Control, Dynamic allocation of resources to UEs in both uplink and downlink (scheduling);
- IP header compression and encryption of user data stream;
- Selection of an MME at UE attachment when no routing to an MME can be determined from the information provided by the UE;
- Routing of User Plane data towards Serving Gateway;
- Scheduling and transmission of paging messages, broadcast information, Public Warning System (PWS) messages;
- Measurement and measurement reporting configuration for mobility and scheduling;
- CSG handling;
- Transport level packet marking in the uplink.

If an FAP connects to the core network (EPC) via the HeNB gateway (HeNB GW), additional requirements should be satisfied, including:

- Discovery of a suitable Serving HeNB GW: an HeNB may be moved from one geographical area to another, and therefore it may need to connect to different HeNB GWs depending on its location. However, at one time, An HeNB shall only connect to a single HeNB GW;
- Selection of an MME at UE attachment is performed at the HeNB GW instead of the HeNB;
- The Tracking Area Code (TAC) and Public Land Mobile Network (PLMN) ID used by the HeNB shall also be supported by the HeNB GW;

Furthermore, an FAP may support LIPA function. LIPA provides access for IP capable UEs connected via an FAP to other IP capable entities in the same IP network. Data traffic for LIPA is expected to not traverse the mobile operator's network except the local mobile operator network components. Signaling traffic will continue to traverse the mobile operator network. Figure 2.10 illustrates how LIPA works in an FAP network.

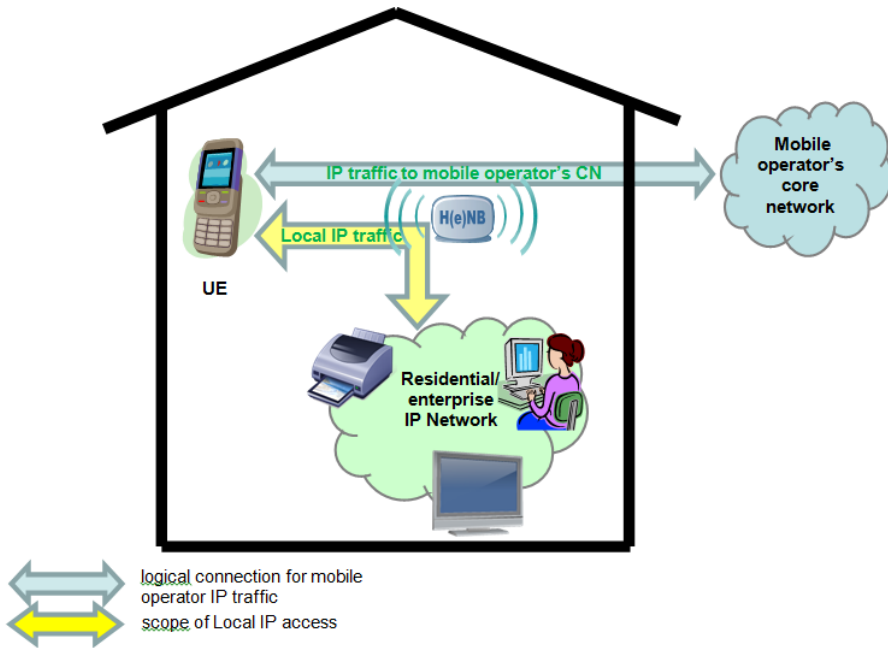


Figure 2.10: LIPA: support local data traffic at HeNB [145].

Since the FAPs can be deployed without network planning (especially in the case of subscriber deployed home FAPs), the network self-organization and self-optimization should be taken special care of. The basic Self-Organized Network (SON) features [118] including e.g. the dynamic configuration of the S1 and X2 interface, and the automatic neighbor relationship function should be supported by FAP. Besides, equipment manufacturers may also implement other SON algorithms in their own FAP products.

## 2.2.2 Business Case for Femto

The Femtocells have been globally deployed to offload the macro network traffic. By the first quarter of 2012, Femtocell have been deployed by 39 mobile network operators in 23 countries. Some of these operators have already deployed hundreds of thousands of Femtocells, including Sprint and AT&T (> 500k), Softbank and SFR (> 100k), and Vodafone [31].

Most of these deployment cases are based on subscriber installed home Femtocells, typically with low upfront fee (Vodafone UK) or even free to users (Softbank, Vodafone GR, SFR). However, the enterprise Femtocell is also supported by many

operators, e.g. T-Mobile, Network Norway, Orange etc. Some operators have even deployed both home and enterprise Femtocells, e.g. Vodafone, Verizon Wireless and Sprint. One can refer to [129] and [130] for the Femtocell deployment case study of AT&T (home Femtocell), and Network Norway (enterprise Femtocell).

Deploying the Femtocells also adds some cost to the operators, especially those who charge low or no fee to their subscribers. However, according to the report from Signal Research Group [131], the network saving by offloading the macrocell network exceeds the cost of Femtocells deployment. Therefore, Femtocell is a profitable technology while providing high data rate.

### 2.2.3 Femto Related Study

The deployment of multiple Femtocells within a graphically limited area achieves high spatial frequency reuse, and hence offers significant capacity gain even in a non-coordinated manner in an overlaid macro network [42,81]. The introduction of Femtocells in an existing macrocell network leads to the so-called HetNet. In HetNet, the co-channel deployed Femtocells create high interference to the macro-layer.

While considering particularly the indoor enterprise Femtocell deployment scenarios, another type of interference has great impact on system performance, namely the inter-Femto interference. The Femto interference management in 3G and 4G Femtocell is studied in [132] and [133], respectively. Both intra- and inter-layer interference should be properly mitigated or avoided. In [81, 134–142], several Inter-Cell Interference Coordination (ICIC) algorithms have been developed to best exploit the benefit of Femtocells. They also motivate our study for small-cell optimization via joint scheduling.

Femtocells typically follow the CSG manner for admission control [143]. CSG provides access to specific UEs only. For a macro-UE in the vicinity of a co-channel deployed Femto access point, it suffers from high Femto-interference and is likely to experience radio link failure. This problem can be solved by using the previously mentioned time/frequency domain resource partitioning algorithms. Furthermore, the downlink transmit power of FAPs and uplink transmit power of UEs connecting to FAPs can also be optimized to minimize the impact on macro layer [144–146]. Furthermore, changing the Femto access policy is also a viable solution, i.e., OSG Femtocells [147–149]. The hybrid access policy could also be used to resolve such a problem while maintaining high throughput for the intended UEs. With the hybrid access policy, a fraction of the resources is configured for OSG, while the rest still follows the CSG mode. In a Femtocell network, neighboring cells can communicate with each other to achieve ICIC through the X2 interface when available [127]. When multiple component carriers are supported via carrier aggregation [150],

the inter-Femto interference can also be managed via the Autonomous Component Carrier Selection (ACCS) function [151].

Although X2 interface allows for ICIC and can improve the system performance, it may not be supported by Femtocells. According to [152] and [153], the baseline assumption is no X2 interface for Femtocell. This assumption is adopted in our study, and hence the focus is on developing uncoordinated algorithms for ICIC.

Many commercial reports and a few technical reports have studied the cost benefit of Femto deployment [154–157]. Some of them deal with the vast area deployment of a large amount of Femtos instead of building new Macro sites. The business case is evaluated as cost savings as a result of reducing the need for new Macro sites. Others pay particular attention to the residential adoption feasibility of Femtos. Those studies focus on how to make pricing strategies that would attract more users to deploy residential Femtos and maximize the total revenue of the operator at the same time.

In our study we will address the inter-cell interference management in indoor enterprise scenarios and the network cost analysis, focusing on comparing the different indoor techniques.

## 2.3 Downlink Transmission and Capacity Limits of Plain DAS and Femto System

In this section we will demonstrate the downlink radio transmission of the distributed antenna system and un-coordinated Femto system when serving an office building. The image in Figure 2.11 shows a scenario of  $N$  spatially distributed AP<sup>6</sup>s serving a number of indoor users. The  $L_i$  denotes for the large-scale pathloss from the  $i^{th}$  AP to one of the users,  $UE_0$ .

The UEs are situated in an in-building area and are surrounded by multiple in-building APs, as shown in Figure 2.11. We assume that all the DAS APs are connected to the same base station sector, therefore a single-cell DAS. Furthermore, we assume the same total number of in-building APs for all indoor systems under comparison.

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<sup>6</sup>The distributed radio element is called an AP to describe the source of the signal in downlink no matter whether it is a Femto access point or a DAS antenna.

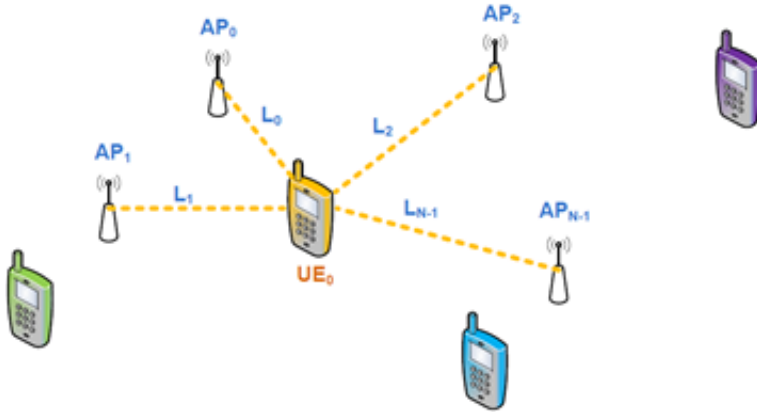


Figure 2.11: Multiple access points and multiple mobile users.

### 2.3.1 DAS

A simulcast DAS with  $N$  APs is demonstrated in Figure 2.12. Assuming single antenna at both remote AP and user equipment, the distributed multiple simulcast APs form a macroscopic MISO channel to the user equipment. In the downlink, the same copies of signal are simultaneously broadcasted by all APs; signal components arriving with different phases at the receiver could add up either constructively or destructively when non-coherent combining is used.

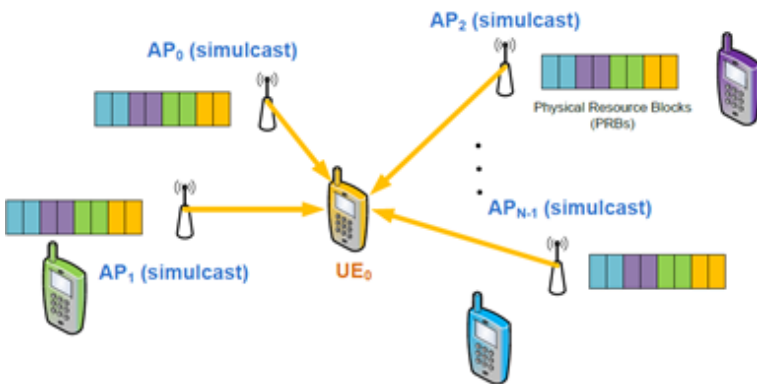


Figure 2.12: The DAS downlink simulcast.

For the Orthogonal Frequency Division Multiplexing (OFDM) signal, the narrow band macroscopic Multiple Input Single Output (MISO) vector channel can be

written as:

$$\mathbf{h} = \left[ \sqrt{L_0}h_0, \sqrt{L_1}h_1, \dots, \sqrt{L_{N-1}}h_{N-1} \right] \quad (2.1)$$

where  $h_i$  denotes i.i.d. small scale fading channel from the  $i$ th distributed AP with  $E[|h_i h_i^*|] = 1$ ;  $L_i = PL_{ref} \cdot d^{-\alpha} \cdot 10^{\lambda_i/10}$  denotes the large scale fading determined by path-loss and shadow fading. The path-loss is distance dependent of  $d$ , and  $\lambda_i$  follows a Normal distribution of variance  $\sigma^2$ . The phase steered transmitted baseband signal vector is expressed by:

$$\mathbf{x} = \left[ g_0 \sqrt{P_0}x, g_1 \sqrt{P_1}x, \dots, g_{N-1} \sqrt{P_{N-1}}x \right]^T \quad (2.2)$$

where  $x$  is the normalized baseband signal  $E[|xx^*|] = 1$ ,  $P_i$  is the transmitting power at the  $i^{th}$  AP, and  $g_i$  is the weighting factor with  $g_i = h_i^*/\sqrt{h_i h_i^*}$ . The received signal is:

$$y = \mathbf{h}\mathbf{x} + z = \sum_{i=0}^{N-1} \sqrt{h_i h_i^*} \sqrt{L_i} \sqrt{P_i} x + z \quad (2.3)$$

where  $z$  is the additive Gaussian noise with variance  $\sigma_n^2$ . The expected average SNR,  $\bar{\gamma}$ , will be:

$$\bar{\gamma} = E \left[ \frac{1}{\sigma_n^2} \sum_{i=0}^{N-1} |h|^2 L_i P_i \right] = E \left[ \frac{1}{\sigma_n^2} \sum_{i=0}^{N-1} L_i P_i \right] \quad (2.4)$$

In reality, phase steering is not applied in most DAS, so the diverse signals from different antenna ports are combined at the mobile antenna before reception and the signal is possible to add up destructively. The mean power of received downlink signal is the sum of the power of individual rays assuming random phase [107].

### 2.3.2 Uncoordinated Femto System

The uncoordinated solution is composed of multiple stand-alone APs with no information exchange between them, which is thus most likely to commit uncoordinated packet scheduling. This is similar to the solution based on Femtocells that some operators plan to offer for the indoor office environment.

For a multi-Femto system with no interference coordination mechanism, referred to as Femto system in the following text, the downlink transmission will suffer from interference from all other active cells operating on the same frequency band. An

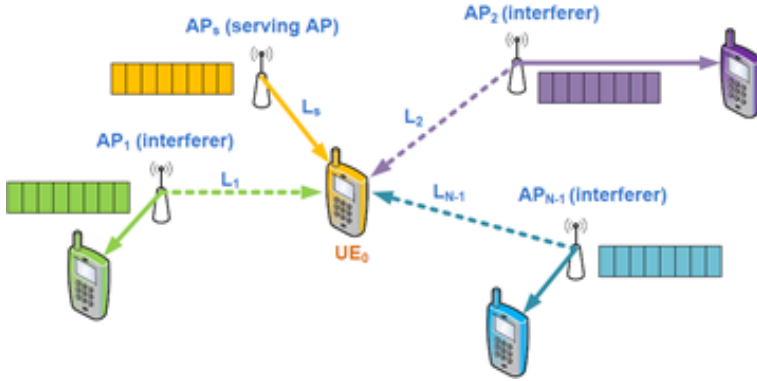


Figure 2.13: Multi-Femto downlink transmission with neighboring cell interference.

example of such a situation is shown in Figure 2.13. In the figure, each user is served by one serving Femtocell. The color-filled blocks represent the physical resource blocks (PRBs) of each individual cell available for MAC layer packet scheduling. The use of different filling colors means that the radio resources are allocated to different users. The subscript indicates properties belonging to the same cell. The solid line shows the useful signal from the serving AP; the dashed lines are interference from surrounding APs. The interference situation is only plotted for  $UE_0$  for simplicity. In a SISO system, the received downlink signal is given by:

$$y = h_s \sqrt{L_s} \sqrt{P_s} x_s + \sum_{i \in \Omega} h_i \sqrt{L_i} \sqrt{P_i} x_i + z \quad (2.5)$$

where the subscript  $s$  means that the properties belong to the serving link;  $x_s$  is the desired signal;  $\Omega$  is the set of co-channel interfering cells, and  $x_i$  is signal from interferer cells. For example, in a fully loaded hard frequency reuse 1 system, there are  $N - 1$  interferers:  $AP_1, AP_2, \dots, AP_{N-1}$ ,  $\Omega = \{1, 2, \dots, N - 1\}$ , as illustrated in Figure 2.13 by dashed lines. The expected average SINR can be written as:

$$\bar{\gamma} = E \left[ \frac{|h_s|^2 L_s P_s}{\sum_{i \in \Omega} |h_i|^2 L_i P_i + \sigma_n^2} \right] \quad (2.6)$$

For cell edge users who receive strong interference from one or more neighboring cells, their poor SINR condition will prevent them from achieving very high data rate.

The simplest form of coordination by resource partitioning and reuse to avoid multi-cell interference is hard frequency reuse. The hard frequency reuse scheme divides the whole spectrum resource into smaller orthogonal portions. Each AP will take a subset of those and avoid overlapping with the nearest neighbor cells. Studies in [158,159] suggest that using hard frequency reuse of factor two, provides



the best performance in the local residential Femto deployments when there is no information exchange between Femtocells.

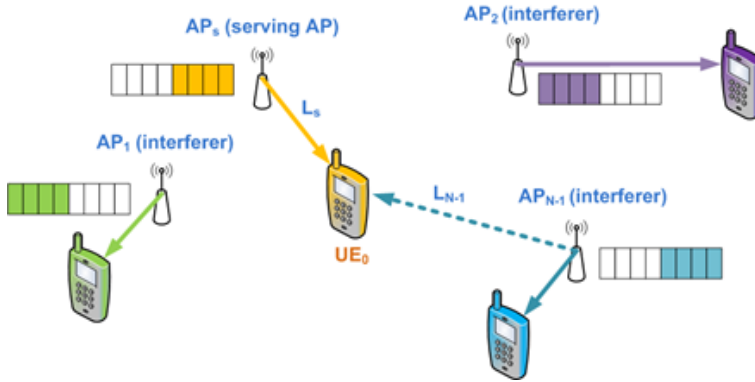


Figure 2.14: Multi-Femto downlink transmission with frequency reuse of factor two.

## 2.4 Intelligent Scheduling System (IDS)

In the rest of the thesis, the radio performance evaluation of different indoor solutions forms one focus of the study. Besides the conventional DAS and Femto system, a centralized coordinated scheduling system is proposed. The proposed system is to provide inter-cell interference avoidance in a multi-cell setup by coordinated MAC layer scheduling.

The centralized coordinated scheduling system is designated to overcome the shortcomings of the DAS and Femto systems. In the DAS, the cell capacity is distributed in a relatively large area where less spatial reuse of spectral resource limits the overall in-building capacity. Meanwhile, the Femto system provides high throughput due to dense multi-cell deployment, but its performance is deteriorated by the severe inter-cell interference.

The centralized coordinated scheduling system employs a structure similar to DAS, which is depicted in Figure 2.15. It can be also called an Intelligent Distributed System (IDS) for its usage of co-located base stations and distributed remote antennas. It has the advantage of bringing multi-cell capacity in a dense deployment as in a Femto system. It also benefits from centralized coordination to cope with the inter-cell interference which is the main contributor to deteriorating the performance of a multi-Femto system.

One way to further increase the DAS capacity is the possibility to reuse available frequency resources, i.e. between remote APs. In the IDS concept each remote element is connected to its own cell with individual cell ID and thus identifiable at the central controller. This allows a centralized coordination of AP transmission and scheduling decisions to be made jointly at the central controller for all cells.

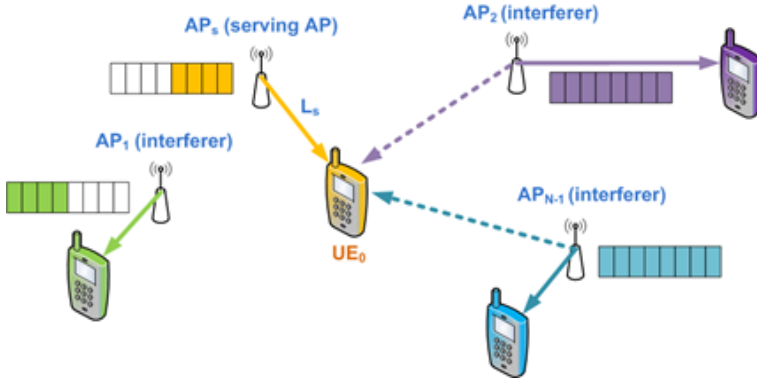


Figure 2.15: The centralized coordinated scheduling system (IDS).

Many previous studies have proposed that some decentralized strategies use soft frequency reuse to reduce inter-cell interference, for example the F-ALOHA [160], ACCS [158]. In those schemes, only part of the total bandwidth is available at each cell. However, the selection of the frequency resources is decoupled from packet scheduling, which leads to random interference reduction for users, i.e., cell edge users will not be guaranteed to have reduced interference all the time, and interference reduction for a user who already has very good signal condition will not lead to increased data rate. We solve this problem in the joint scheduling scheme by the two operations below.

In the downlink, the average path loss values to nearby APs can be estimated by the user using reference signals transmitted from individual APs. The path loss estimation can then be used for both cell selection and coordinated transmission:

1. Strong Interferer Selection: For each user, a group of strong interfering cells is identified. This information is then passed on to the joint scheduler.
2. Joint scheduling: A central controller is assumed where the packet scheduling of multiple cells can be jointly committed. The joint scheduling of multiple cells makes sure that frequency resources allocated to a user will not be reused by the user's recorded strong interfering cells at the same transmission time slot.

The average SINR with the joint scheduling can still be calculated by Eq (2.6), but with a reduced  $\Omega$  excluding the strong interferers. In this way, the soft frequency reuse is achieved by explicitly mitigating the transmission on certain frequency resources and sacrificing these resources for better user SINR conditions. The multi-cell joint scheduling procedure is described in detail in Appendix A section A.1.

In the coordinated system, the strong interferer selection criterion is crucial for the system performance because it determines the final interference level and the amount of resources available for reuse. However, the realization of the algorithm depends on the type of MAC-layer packet scheduler applied. In the following chapter, we will propose two selection criterion alternatives as we explore the system performance by simulation.

# System Performance Evaluation with Full Load Traffic

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## 3.1 Introduction

After the introduction to the dedicated indoor mobile systems provided in Chapter 2, the radio performance of these in-building wireless systems will be demonstrated and compared in this chapter. The performance is obtained by system-level simulation in an LTE context. We aim at evaluating the competency of the different indoor systems when dealing with the foreseeable high-speed, high volume indoor mobile data demand which is expected to occur in the future 5-10 years. The full buffer traffic model is adopted in this chapter, which assumes that each user always has data to transmit or receive. It leads to the worst case scenario with full inter-cell interferences, and can well model the system performance during traffic peak hours.

Due to the experienced unbalanced uplink-versus-downlink traffic volume, we focus primarily on the downlink performance where the majority of data traffic will be generated. However, in the later part of this chapter, we show that with the help of the proper uplink power control scheme and the appropriate parameter settings, high uplink capacity can be achieved. The uplink will not become the bottleneck of the data network. For the analysis in both downlink and uplink,

we explicitly concentrate on indoor user experience and indoor users only. The impact of indoor-to-outdoor interference on the radio performance and admission control of outdoor users is beyond the scope of this study.

In the system simulation, a three-storage enterprise building model is used. The building model is retrieved from a practical office building; the in-building pathloss value is derived from real-life measurement. To verify the universality of the obtained result, a general office building model described in the WINNER II project is used to run the same set of simulations. The result of the latter case is presented in Appendix C, which confirms the result we get with the site-specific building model. Simulation methodology (Monte-Carlo simulation) and detailed simulation assumptions are described in Appendix B.

## 3.2 Performance with Packet Scheduler Adopting the Equal-share Principle

The equal-share principle is adopted by many prevalent packet schedulers. Two good examples are the round-robin [161] and the proportional fair [162] scheduler. With such a scheduler, each cell tries to assign frequency/time resources equally to its users in a long-term (relative to units of TTIs) average. The received quality of service in terms of user throughput depends merely upon each user's SINR condition and the number of active users corresponding to the same serving cell.

The mathematical expression of the user average SNR/SINR distribution in an in-building environment is hard to write in a closed form. Instead, they are plotted in Figure 3.1 for DAS and Femto systems with Hard Frequency Reuse (HFR) 1 and 2. The plain DAS and Femto system with HFR was introduced and explained in Chapter 2.

The figure clearly shows superior SINR condition of the DAS to Femto system. The reason is that the downlink received signal quality is deteriorated by the noise and cross-layer interference, i.e. the interference from the outdoor macro sites. The user SINR becomes better and better as more radio sources are added in. However, the Femto system experiences not only the cross layer interference, but also the inter-Femto interference, which is a stronger contributor to the overall interference power due to the shortened distance. In the case where the SINR is plotted, as more FAPs deployed in the same building, more interference sources are added in, which results in worse SINR distribution.

For a resource equal-shared scheduler, the average LTE system throughput can be estimated by computing directly from the SINR distribution, using the modified

### 3.2 Performance with Packet Scheduler Adopting the Equal-share Principle41

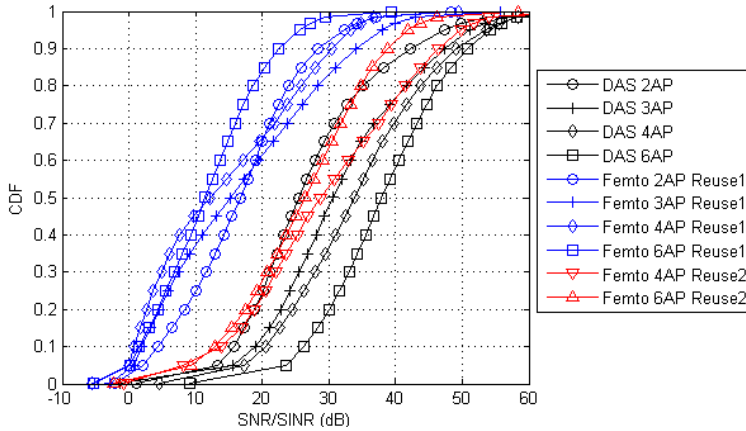


Figure 3.1: User average SNR/SINR distribution, site-specific building, with macro interference.

Shannon formula [163]:

$$C = \frac{N}{R} \cdot B \cdot \int_{\bar{\gamma}} \min \left\{ \beta \cdot \log_2 \left( 1 + \frac{\bar{\gamma}}{\alpha} \right), \mu_{max} \right\} \cdot p_{SINR}(\bar{\gamma}) d\bar{\gamma} \quad (3.1)$$

where  $p_{SINR}(\bar{\gamma})$  is the probability density function of user average SINR;  $B$  is the system bandwidth;  $\mu_{max}$  is the maximum achievable spectral efficiency;  $R \in \{1, 2\}$  is the reuse factor;  $N$  is the number of cells, which has the value of 1 in DAS. In a SISO system with channel-unaware scheduling,  $\alpha$  is equal to 2,  $\beta$  equals to 0.56. With 64QAM and 9/10 coding rate being the highest modulation coding scheme, the system average spectrum efficiency and overall throughput for 10MHz bandwidth is shown in Figure 3.2.

The macro interference has a greater impact on deteriorating the system performance when the number of in-building APs is low; however, this effect is diminished by increasing the number of in-building APs. When 6 APs are deployed in the building, the performance of the indoor system is almost the same with and without macro interference. The performance of the DAS saturates and is upper-bounded by the single-cell peak data rate of 50Mbps, which is given by  $B \cdot \mu_{max}$ . Although the Femto system achieves higher system throughput (Figure 3.2, figure to the right) because it increases the available resources by reusing the resource between APs; the average spectral efficiency is quite low compared to the DAS (Figure 3.2, figure to the left) which suggests that the excessive radio resources are not utilized efficiently. By using frequency reuse 2, the average spectrum efficiency is largely improved for the Femto system compared to using reuse 1. However, the tradeoff is that the available resource is reduced by half. The combined effect is

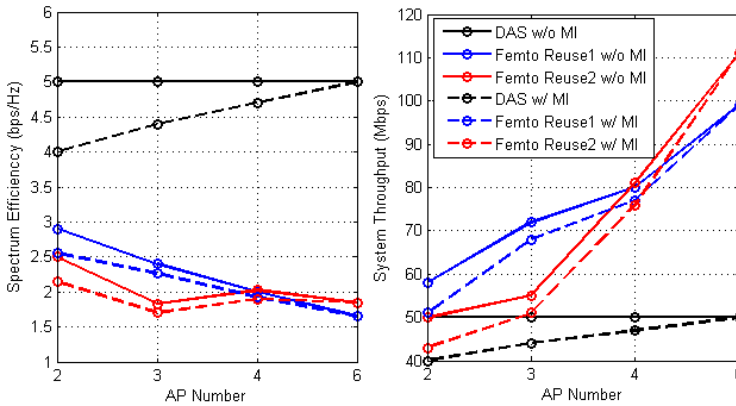


Figure 3.2: System capacity of SISO DAS and Femto systems of different AP numbers.

that the reuse 2 Femto system does not always outperform reuse 1 system in terms of system throughput unless it can double the spectrum efficiency achieved by the reuse 1 system.

Other interference management methods have to be found to more effectively reduce the inter-cell interference in a dense multi-cell system which has less penalty on the useful spectrum resource. We have introduced the idea of the centralized coordinated scheduling system (IDS) in Chapter 2, and in the same chapter discussed variant interference avoidance schemes for multi-Femto systems. In the performance evaluation and comparison, we select a randomized interference avoidance scheme for the multi-Femto system which is called fixed-fractional reuse. In the following section, we provide description of the strong interferer detection method for IDS with an equal-share scheduler and the fixed-fractional reuse scheme, as well as a summary of all studied indoor systems before presenting the simulation results.

### 3.2.1 Selected interference avoidance and management methods

**the IDS with Equal-share Scheduler: strong interferer determined by fixed threshold**

In the previous chapter, we have briefly introduced the basic operation principle of the coordinated scheduling procedure, such as:

1. Strong Interferer Selection: For each user, a group of strong interfer-

### 3.2 Performance with Packet Scheduler Adopting the Equal-share Principle43

ing cells is identified. This information is then passed on to the joint scheduler.

2. Joint scheduling: A central controller is assumed where the packet scheduling of multiple cells can be jointly committed. The joint scheduling of multiple cells makes sure that frequency resources allocated to a user will not be reused by the user's recorded strong interfering cells at the same transmission time slot.

The scheme to determine the strong interferer group is crucial to the performance of the coordinated system. With equal-share scheduler, we introduce a fixed threshold to improve the user SINR.

A simple approach to decide the strong interferers is based on a fixed threshold  $\gamma_{th}$ .<sup>1</sup> The measured average channel gain (average channel gain is obtained by RSRP) of each neighboring cell is compared pair-wise with the serving cell. A cell will be considered as a strong interferer if the difference of channel gain is below the predefined threshold as expressed below,

```
for  $i = 1, 2, \dots, N_{cell}(i \neq s)$ 
  if  $|G_s - G_i| < \gamma_{th}$ 
    add cell  $i$  to the user's strong interferer set  $\Omega$ 
  end
end
```

where  $N_{cell}$  is the number of coordinated cells,  $G$  is the average channel gain and the subscript  $s$  stands for the serving cell. Different threshold values (3dB, 6dB, 10dB) are used in the simulation. We will only show the performance results with the threshold value that gives the best overall performance, i.e. 10dB.

#### Fixed-fractional Reuse (FFR) Femto System

In this scheme, only a fraction of the frequency resource, or the Physical Resource Block (PRB)s, is utilized for downlink transmission. The rest of the PRBs will not be scheduled and will be assigned no power for data transmission thus generating less interference to users in other cells. The selection of available PRBs is randomized per cell per TTI, so that the reduction of inter-cell interference is also randomized. Figure 3.3(c) illustrates, in case-3, an example of PRB allocation of the FFR Femto system. In the figure and in the following simulation, a fixed fraction of 0.7 (number of PRBs for scheduling divided by total number of PRBs given by available bandwidth) is used which gives the best performance among all tested values (0.6, 0.7, 0.8 and 0.9).

---

<sup>1</sup>This system is therefore denoted by  $IDS(*)$  in the later simulation results, where  $*$  represents the value of the threshold in dB.



A summary of the investigated systems in this section is given in both Table 3.1 and Figure 3.3. The three different cases illustrated in Figure 3.3(c) correspond to the three options listed in Table 3.1 for the Femto system. The Femto system with HFR 1 is denoted "the Femto system" or "the plain Femto system" in the rest of the text.

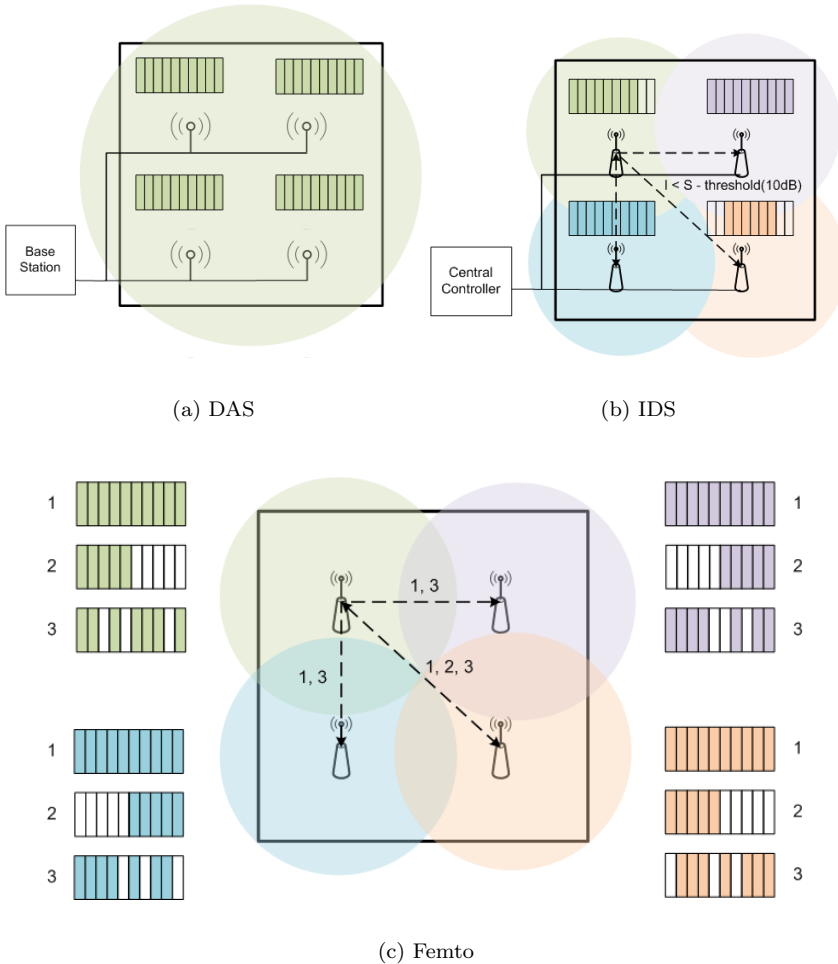


Figure 3.3: Illustrative summary of studied indoor system with different schedulers.

Table 3.1: Summary of studied indoor systems.

Solution	DAS	Femto			IDS
		Option 1. HFR 1	Option 2. HFR 2	Option 3. FFR 0.7	Fixed- threshold
Cell configuration	Single-cell with BW sharing between APs	Multi-cell: with BW sharing per AP	Multi-cell: with BW sharing every second AP	Multi-cell: with randomized partial BW sharing per AP	Multi-cell with partial BW sharing per AP, depending on interference threshold
Interference source	Macro layer	Macro layer and other APs (full interference)	Macro layer and other APs (reduced interference in a planned manner)	Macro layer and other APs (reduced interference in a random manner)	Macro layer and other APs (depending on interference threshold)

### 3.2.2 System Performance and Comparison

In the previous sections, we have had an overview of the system performance with an equal-share scheduler by analytical estimation. Poor SINR was shown for the Femto system due to severe inter-cell interference, but higher capacity due to spatial reuse of frequency resource. In this section, the Monte-Carlo simulation was done with the same building model and large-scale pathloss data. For multi-antenna techniques, we consider two receiving antennas at the user equipment and single antenna at the transmitter side. The 1-by-2 SIMO system is simulated with standardized receiver diversity scheme defined by 3GPP. The co-channel deployment with the outdoor macro cell is assumed; detailed description of assumptions can be found in Appendix B.

Other than the overall system throughput, another Key Performance Indicator (KPI) is used to evaluate and compare different systems. Individual user satisfaction is considered another important measure of service quality. In the up-coming years with a huge amount of data traffic generated by mobile users, the expected downloading speed of files, web-pages or videos increases accordingly. Users are more concerned with their own service experience on the experienced data speed. Low access speed to online web-pages or videos leads to dissatisfied users, which the service provider is trying to avoid. It is highly valued to support as many users as possible and at the same time, to guarantee a certain satisfaction level by providing satisfying data rate to almost all users, allowing a small outage rate.



Figure 3.4: Comparison of maximum simultaneously supportable number of QoS users of different systems according to different number of APs.

The other KPI is defined as the maximum number of users that a certain system can support provided that at least 95% of the users receive data speed faster than a minimum target, below which the user will be considered as dissatisfied. This KPI is similar to a 5% outage performance, but demonstrates more clearly the system capacity on supporting users with certain QoS requirement. We assume all users require to receive a minimum data rate of 2 Mbps. The performance of the maximum simultaneously supportable number of users (denoted as UE for short in the following figures) is presented in Figure 3.4. The result of the overall system throughput is shown in Figure 3.5 for 2, 3, 4 and 6 APs deployment, respectively. In the figures, the blue bar plot is the real value of the corresponding KPI, and the red line shows the relative performance gain compared to the Femto system with the same AP number.

As to the number of supported QoS users, the DAS offers a good performance, but as we can see later, it performs poorly in system throughput. The plain Femto

### 3.2 Performance with Packet Scheduler Adopting the Equal-share Principle47

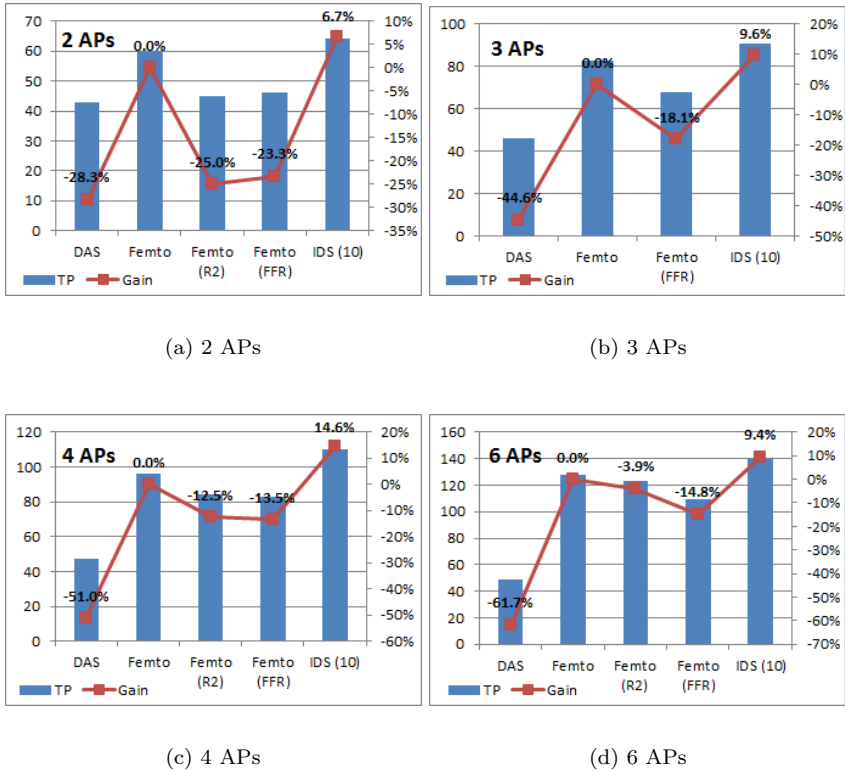


Figure 3.5: Comparison of overall system throughput of different systems according to different number of APs.

system is quite inefficient at supporting QoS users, which has the smallest number of supported users shown in Figure 3.4. IDS gives the best performance among all the investigated systems. Regardless of the number of APs deployed, the IDS always supports 2 times more QoS users than the plain Femto system. The HFR 2 and FFR scheme can both help improve the performance of the Femto system by up to (or more than) 50%.

The system throughput shown in Figure 3.5 aligns well with that by analytical prediction in Figure 3.2, in the sense of the relative performance comparing the DAS and the Femto system with HFR 1 and 2. The only exception is the Femto HFR 2 performance with 6 APs. Here, the Femto HFR 2 performs slightly worse than the plain Femto system, which is different with the previous result. This difference is made by the second receiver antenna (1-by-2 SIMO versus SISO) at the user side which brings about additional diversity gain. This gain on SINR is most beneficial for users with poor SINR.

Overall, the plain Femto system achieves high system throughput, while the IDS gives the highest throughput which is on average 10% higher than the plain Femto system. The Femto HFR 2 and FFR system offer similar performance, and do not perform as good as the plain Femto system. The drawback of this fractional frequency reuse system can be read from the figure. That is, it suffers from 3.5% to 25% degradation in average system throughput than the plain Femto system. The reason is that, although the partial frequency usage improves the SINR condition, this upgrade is insufficient to compensate for the loss of available resources which can be allocated to the users with high SINR. Furthermore, in the FFR scheme, the selection of the frequency resources is decoupled from packet scheduling, which leads to random interference reduction for users, i.e., cell edge users will not be guaranteed to have reduced interference all the time, and interference reduction for a user who already has very good signal condition will not lead to increased data rate.

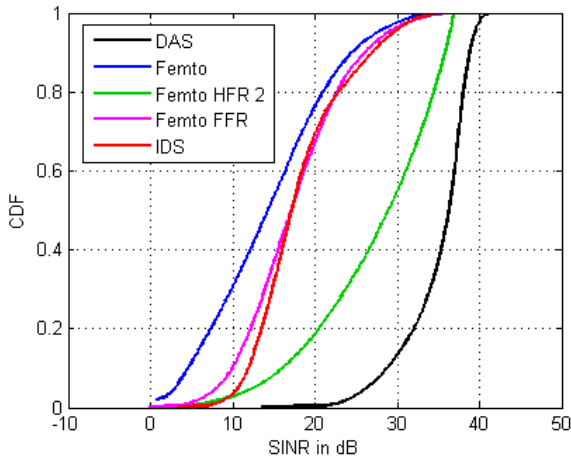


Figure 3.6: Cumulative distribution function of user average SINR of 6 APs.

To better interpret the results, the cumulative distribution function of user average SINR is plotted for each system with 6 APs in Figure 3.6. The IDS reduces interference according to the predefined threshold of 10dB. Thus, its average user SINR is attempting to be higher than 10dB. The FFR scheme takes advantage from randomized reduction of inter-cell interference, the improvement of SINR is more obvious at the lower region of SINR distribution.

The average user throughput distribution is shown in Figure 3.7. The deficiency of the FFR scheme can be clearly seen throughout the result obtained with a fixed number of users in the system, shown in Figure 3.7(b). Although the FFR improves the user SINR, which gives particular benefit to the cell-edge users (reflected by better throughput at the lower end), the mean user throughput is less than the

### 3.2 Performance with Packet Scheduler Adopting the Equal-share Principle49

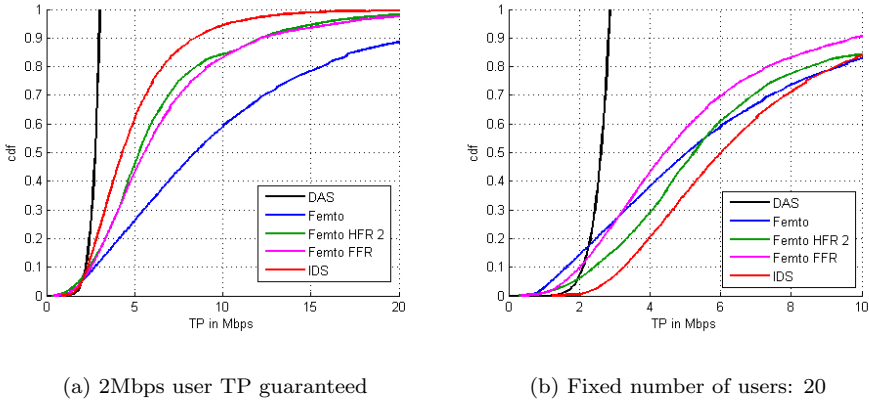


Figure 3.7: Cumulative distribution function of user average throughput of 6 APs, fixed number of 20 users.

plain Femto system because less spectrum resource is available for scheduling. The HFR 2 scheme shares the same problem. The IDS is seen to be able to keep the best balance between reduced SINR and available spectrum resource. With much improved 5% outage user throughput, it maintains a very high mean user throughput even compared to the plain Femto system.

The average user throughput distribution shown in Figure 3.7(a) assumes that each system is serving the maximum number of QoS user provided that no more than 5% of the users get a data speed slower than 2Mbps. The average user throughput of the multi-cell systems, especially the Femto system, covers a wide range up to 30Mbps. More than 20% of users enjoy excessive high throughput of more than 15Mbps. This figure also reveals why DAS can support a large number of high speed users, but offers low system throughput. Due to the superb user SINR of the DAS, each user achieves the same high spectrum efficiency. With an equal-share scheduler, all users get a quite similar throughput. There is no user with excessively high throughput, neither extremely low throughput.

#### 3.2.3 Performance sensitivity to AP placement

In the real-life deployments, the actual location of the installed indoor APs is affected by many factors, which can be insufficient radio planning, unavailability of power supply or cable connection, hazard areas difficult for installing and many others. These inevitable conditions may lead to a non-optimal placement of APs for the in-building system. The non-optimal placement, illustrated in Figure B.5,

as opposed to the planned placement, illustrated in Figure B.4, is also simulated. This scenario is used to test whether the performance of each system will degrade due to non-optimal AP placement; and if so, how bad will the situation be.

The influence of a non-optimal AP placement is examined for systems with 6 APs. The results are shown in Figure 3.8 and in Figure 3.9. The values on both figures represent the performance gain of each system compared to the plain Femto system. When the value is a negative number, it means the performance of the corresponding system is worse than the plain Femto system.

Seen from the figures, the system performance is shown to be stable (curves overlapping in both placement scenarios) for most systems except for Femto with HFR 2. With the non-optimal placement of APs, the performance of the Femto HFR 2 system degrades by 15% on supported user number and 60% on system throughput. Around 10% reduction of the supported user number is witnessed for the plain Femto system and only 5% for the IDS system.

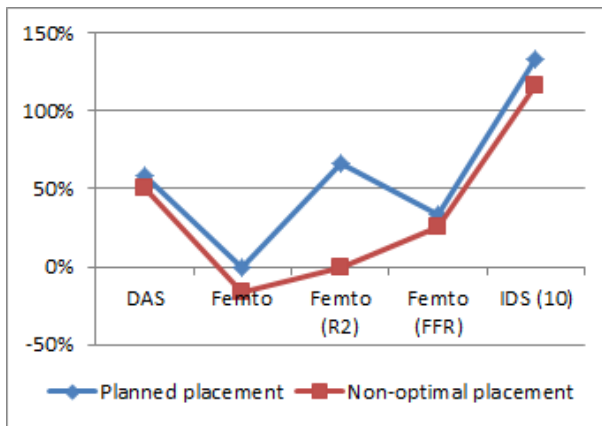


Figure 3.8: Performance degradation of maximum simultaneously supported QoS users by non-optimal placement of 6 APs.

When the AP placement is not well planned, the advantage of the Femto HFR 2 system over the plain Femto system disappears. A non-optimal placement of APs may also be due to the irregular shape or floor plan of the building, which cannot be overcome by radio planning. In such cases, with the ease to be implemented in modern base stations, the FFR scheme may be a good substitute for the HFR 2 scheme.

A illustrative performance summary of the variant indoor systems was made in Figure 3.10.

Whenever it is feasible, the IDS system is the preferred solution among all the

### 3.2 Performance with Packet Scheduler Adopting the Equal-share Principle<sup>51</sup>

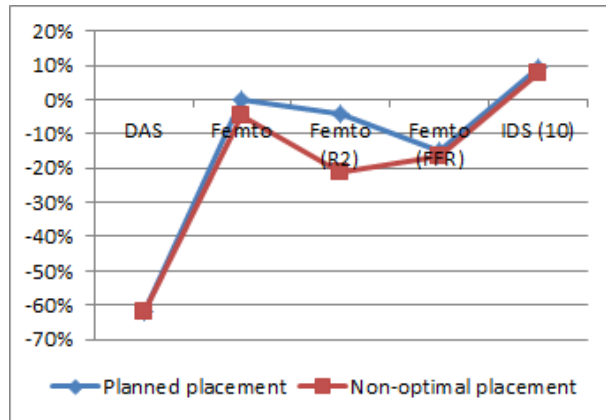


Figure 3.9: Performance degradation of overall system throughput by non-optimal placement of 6 APs.

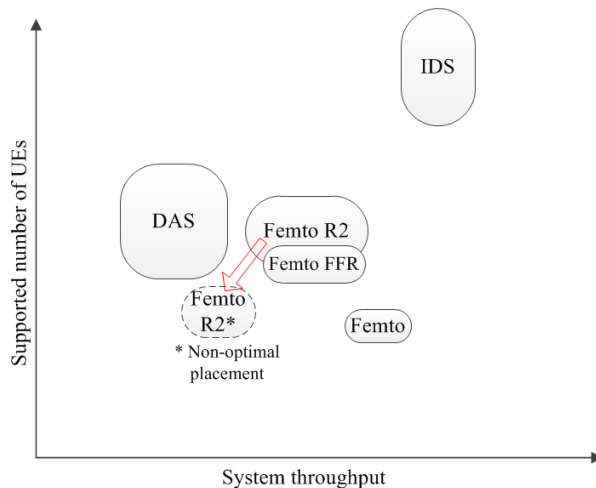


Figure 3.10: Summary of indoor system performance with the equal-share scheduler.

others for providing high throughput for the largest number of users. The Femto system with FFR or HFR 2 can be a compromising solution between the DAS and the plain Femto system. These two schemes suffer from less than 15% decreased system throughput than the plain Femto, but support almost as many QoS users as the DAS does. When using Femto HFR 2, a good radio planning of the AP locations is required, otherwise, the FFR scheme will be a better solution.



### 3.3 Performance with Quality-Guaranteed Scheduler

#### 3.3.1 The Quality-Guaranteed (QG) scheduler

The performance of the multi-cell system is limited by inter-cell interference. With an equal-share scheduler, cell-center users with high SINR and cell-edge users with low SINR share the same amount of radio resource, which leads to polarized throughput: while cell-edge users are discontented with low throughput, users in the close vicinity of the APs enjoy excessively high throughput. With the goal of serving as many users as possible with guaranteed minimum data rate in mind, we try to balance the user throughput by allocating more spectrum resources to users experiencing poor SINR. In this way, the allocation of spectrum resource is biased towards cell-edge users who experience poor SINR condition and improves the throughput of these users. Meanwhile, the drawback is that the resource available for high SINR users will in turn be reduced, which will lead to a cut in the overall system throughput. There are many alternative ways of realizing a QG packet scheduler. One alternative is studied in [164], in which the results show highly improved performance in terms of outage rate and the supported QoS users.

The QG scheduler in our study adopts a different approach as we assume that a transparent Time Domain Packet Scheduler (TDPS) is used. In short<sup>2</sup>, the QG scheduler estimates the amount of spectrum resources needed by each user to achieve its required minimum throughput. The calculation is done by making use of the wideband SINR estimation obtained by user channel measurement. Then the scheduler tries to assign the required number of PRBs to each user. The procedure starts from the user with lowest spectrum request to the user with highest spectrum request until there is no PRBs left, or until all the users belonging to the cell are assigned. If all cell users are successfully assigned with the needed amount of spectrum resource, the QG scheduler will then distribute the unassigned PRBs, if any, equally among all users. We refer to this QG algorithm as full-load QG, or QG in short form, reflecting that it assigns the whole system bandwidth for DL transmission. An illustration of an example is given in Figure 3.11.

#### 3.3.2 Dynamic load Femto system and IDAS with QG scheduler

**The IDS with QG Scheduler: an alternative way to determine the strong interferers**

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<sup>2</sup>Detailed description of how to estimate the needed number of PRBs per user and the operation of the coordinated scheduling is available in Appendix A.

With the equal-share scheduler, a fixed threshold is used to help determine the strong interferer set for each user. This criterion blindly increases the user SINR without considering the spectrum consumption increment on the other cells. It may result in degraded throughput because the improvement made on the user SINR is not enough to compensate for the loss in spectrum resource.

With the QG scheduler, for each user, a minimum amount of bandwidth has to be allocated to guarantee its minimum required throughput. The amount of bandwidth is equivalent to the number of PRBs in an OFDMA system. The modified Shannon formula in [163] offers an LTE system-level estimation of achievable spectral efficiency. It provides a simple estimation from per user average SINR to spectral efficiency taking system constraint and imperfections into account. So that the needed RB number can be estimated by Equation 3.2,

$$\begin{aligned} \lambda_k(\bar{\gamma}) &= \left\lceil \frac{X_k \times T}{\mu_k \times B} \right\rceil \\ &= \left\lceil \frac{X_k \times T}{\beta \times \log_2(1 + \frac{\bar{\gamma}}{\alpha}) \times B} \right\rceil \end{aligned} \quad (3.2)$$

where  $X_k$  is defined as the target QoS throughput of user  $k$  in *bps*;  $T$  as the length of time interval of a scheduling instance (a Transmission Time Interval (TTI), normally 1ms);  $B$  as the effective bandwidth per PRB;  $\mu_k$  as the average achievable spectrum efficiency throughout the whole available bandwidth; the value of  $\alpha$  and  $\beta$  depends on the system configuration which can be found in [163].

A reasonable way to boost system capacity is by maximizing the individual effective spectrum efficiency per PRB. The effective spectrum efficiency is defined as the achievable throughput of a user divided by the total bandwidth it takes up, including not only that on its serving cell, but also the corresponding blocked PRBs on the other cells. The initiative is the same as using the least number of PRBs for each user to achieve the same required data rate. The actual consumed number of PRBs for each user must also take into account the number of its indicated interferer cells (denoted by  $L_\Omega$ ), because the same amount of PRBs will not be reused in those cells:

$$\lambda_{k,actual} = \lambda_k \times (L_\Omega + 1) \quad (3.3)$$

The solution then requires, among all possible compositions of the strong interferer set ( $\Omega$ ), to find the one that gives the minimum  $\lambda_{k,actual}$ . For the  $N - 1$  potential interferers in a  $N$ -cell system, there are potentially  $2^{N-1}$

distinctive possibilities of  $\Omega$ . Nevertheless, we do not have to consider all of them. Instead, for each possible  $L_\Omega$  value (ranging from 0 to  $N - 1$ ), we know that the highest SINR can be obtained by eliminating the strongest  $L_\Omega$  interferers. Then for each  $L_\Omega$  value only one  $\Omega$  set composed of the first  $L_\Omega$  strongest interferers is to be tested.

The algorithm calculates, for every possible  $\Omega$  set, the total number of consumed PRBs. If multiple sets of  $\Omega$  result in the same number of consumed PRBs, the one with the largest  $L_\Omega$  will be selected. For user  $k$ , if the APs can be ordered such that  $G_s \geq G_{j_1} \geq \dots \geq G_{j_{N-1}}$  ( $G_j$  is the average channel gain from cell  $j$  to user  $k$ ), the algorithm can be expressed by:

$$\begin{aligned} \Omega_k &= \Omega = 0 \\ \bar{\gamma} &= E \left[ \frac{|h_s|^2 \times G_s \times P_s}{\sum_{i \in \{1, 2, \dots, N\}, i \neq s} |h_i|^2 \times G_i \times P_i + \sigma_n^2} \right] \\ \lambda_{k, \min}(\bar{\gamma}) &= \left\lceil \frac{X_k \times T}{\beta \times \log_2(1 + \frac{\bar{\gamma}}{\alpha}) \times B} \right\rceil \\ \text{for } L &= 1, 2, \dots, N - 1 \\ \Omega &= \{j_1, \dots, j_L\} \\ \bar{\gamma} &= E \left[ \frac{|h_s|^2 \times G_s \times P_s}{\sum_{i \in \bar{\Omega}, i \neq s} |h_i|^2 \times G_i \times P_i + \sigma_n^2} \right] \\ \lambda_k(\bar{\gamma}) &= \left\lceil \frac{X_k \times T}{\beta \times \log_2(1 + \frac{\bar{\gamma}}{\alpha}) \times B} \right\rceil \\ \text{if } \lambda_k \times (L + 1) &\leq \lambda_{k, \min} \\ \lambda_{k, \min} &= \lambda_k \times (L + 1) \\ \Omega_k &= \Omega \\ \text{end} \\ \text{end} \end{aligned}$$

where  $\Omega_k$  is the strong interferer set for user  $k$ . The calculation of  $\bar{\gamma}$  and  $\lambda_k$  and the explanation of the other denotions follows the same as in Equation 2.6 and Equation 3.3.

### Dynamic reuse (DR) Femto system

In the beginning of this section, the QG scheduler is introduced. We refer to this QG algorithm as full-load QG, or QG in short form, reflecting the fact that it assigns the whole system bandwidth for DL transmission. However, due to the uneven load of different cells, there will be users assigned with a larger amount of PRBs in a light-loaded cell than they actually need to achieve the target data rate. These aggressive users eat up unnecessary resources and generate additional interference to other users. To aim at a constant data rate of 2 Mbps, i.e. to provide streaming-like service, we

introduce the so-called dynamic fractional reuse (DR) scheme on top of the QG scheduler. This scheme reduces the interference level from one cell to the others and saves room for accommodating more users in the whole system.

The DR scheme keeps the remaining PRBs unassigned after all the users have been allocated their minimum required bandwidth, shown in Figure 3.11 as "dynamic load". Those unassigned PRBs from each cell appearing in random manner, will introduce randomized interference reduction in the multi-Femto system.

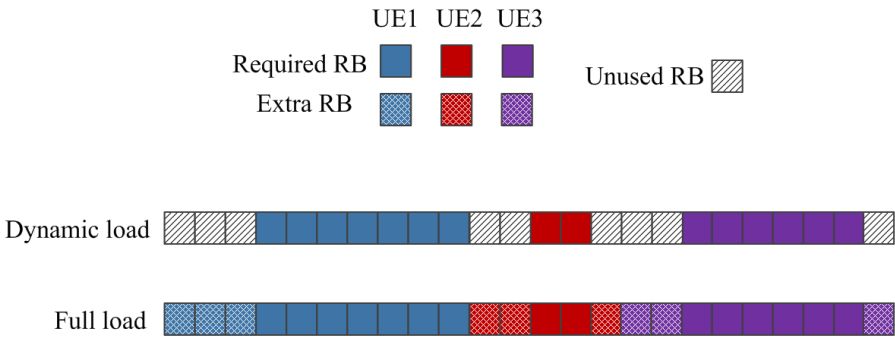


Figure 3.11: Demonstration of the quality-guarantee scheduler.

### 3.3.3 Performance with the QG scheduler

Assuming that each AP is equipped with two transmitting antennas, and correspondingly two receive antennas are used at the user equipment, a 2-by-2 MIMO system, the performance of each system with different AP numbers is shown in Figure 3.12 and Figure 3.13<sup>3</sup>. The gain by applying a QG scheduler compared to the equal-share scheduler is presented in Figure 3.14.

Comparing among all indoor systems, the best performance is still given by the centralized coordinated scheduling system, the IDS. Although the gain provided by the IDS is reduced compared to using an equal-share scheduler, it still achieves an average of 10% of gain over all the other systems. Furthermore, in the later section we will show that its performance is more robust for different AP placements than the other multi-cell systems. The IDS without a fixed threshold has an overall better performance than the IDS with a fixed threshold, IDS(10). It obtains as high system throughput as the IDS with 10dB threshold, but achieves up to 13% better performance in supported user number.

<sup>3</sup>The performance results of the QG scheduler with 1-by-2 SIMO are presented in C.2. The performance results of the equal-share scheduler with 2-by-2 MIMO is presented in C.1

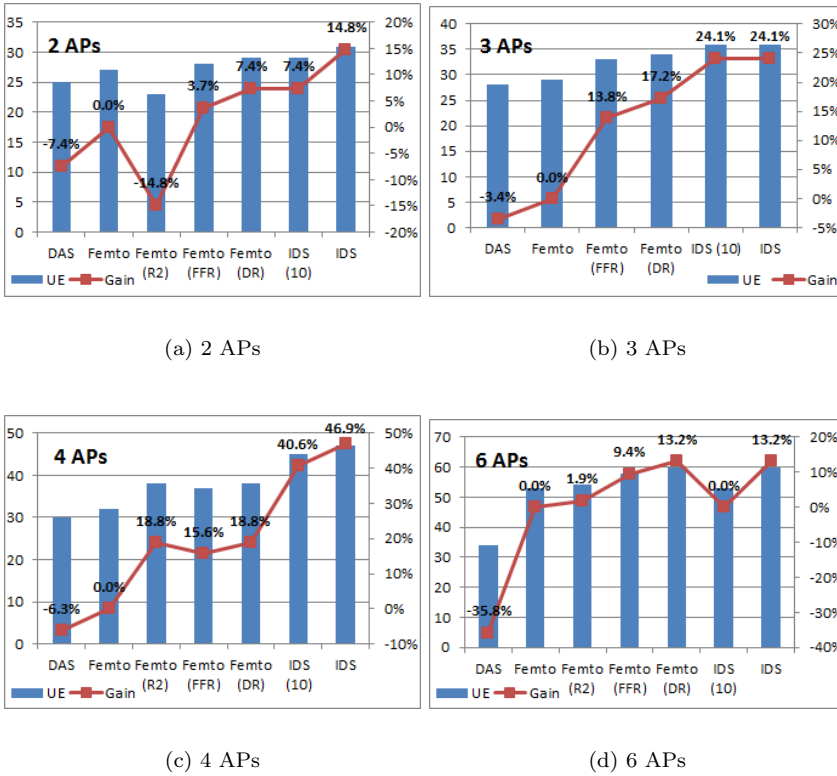


Figure 3.12: Comparison of maximum simultaneously supportable number of QoS users of different systems according to different numbers of APs.

The QG scheduler is efficient in increasing the number of supported QoS users where excessive spectrum resources are available, which is the case for the multi-cell systems. By using the QG scheduler, the Femto system not only benefits from a large gain in supported user number, but also keeps its advantage on the high system throughput. It now outperforms the DAS on both KPIs. The DAS with any number of APs performs worse than all the other multi-cell systems. The FFR and DR scheme for the Femto system tries to make a further compromise between the system throughput and supported user number. They both promote the supported user number by around 10%, but suffer from a similar degree of loss in the system throughput.

The contribution of the 2-by-2 MIMO technique lies in the fact that the additional diversity gain effectively improves the achievable spectral efficiency of cell edge users in the Femto system; and Femto HFR 2 system has no longer absolute advantages comparing to the plain Femto system, which is in contrast to the 1-by-

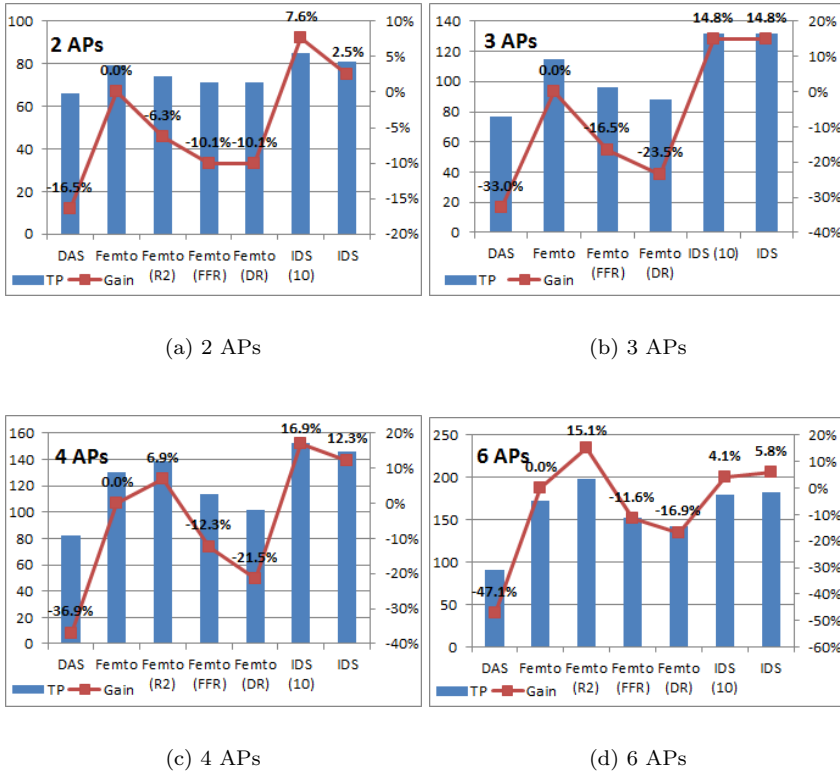


Figure 3.13: Comparison of overall system throughput of different systems according to different numbers of APs.

2 SIMO scenario, especially with a high number of APs (the 1-by-2 SIMO results can be referred to in Chapter C.2).

Figure 3.14 shows the performance gain of using the QG scheduler versus the equal-share scheduler. The result indicates that compared to using the equal-share scheduler, the average system throughput is decreased by using the QG scheduler. However, the overall decrease is relatively small if compared to the increase in the number of supported users: there is 10% loss in the worst case for both I-DS and any Femto system while the gain in the supported number of users is over 30% up to 140%. The DAS has almost no loss in the overall system throughput, but by using the QG scheduler, it embraces 30% of increase in supported user number. The gain (or loss) is quite similar in 1-by-2 SIMO case for all systems, which is demonstrated by the dashed line.

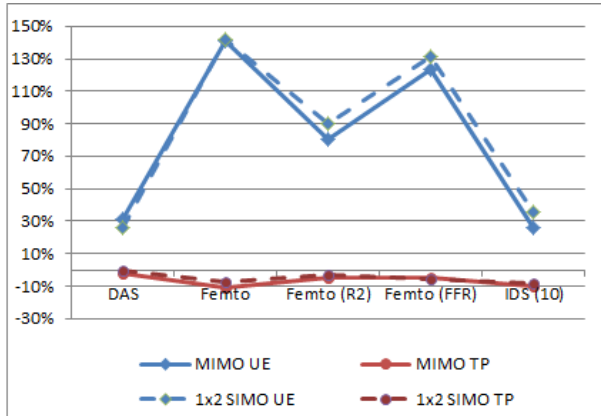


Figure 3.14: Performance gain of using QG scheduler versus equal-share scheduler.

### 3.3.4 Performance sensitivity to AP placement

The relative performance gain of each system compared to the plain Femto system is shown in Figure 3.15 for two AP placement scenarios. The solid line represents the 2-by-2 MIMO case<sup>4</sup>, and the dashed line represents the 1-by-2 SIMO case<sup>5</sup>.

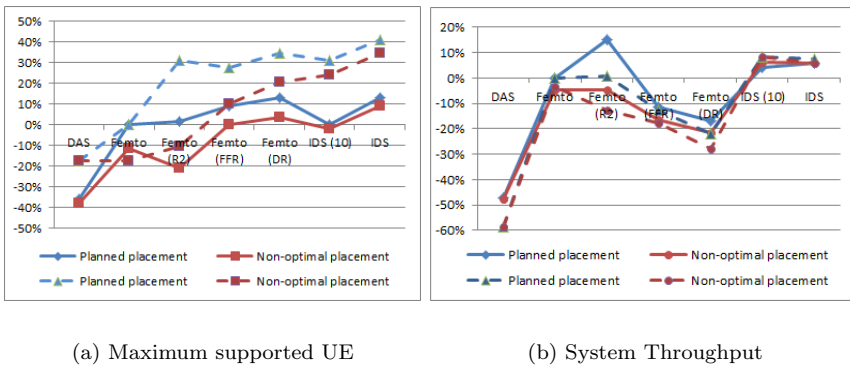


Figure 3.15: Performance degradation of maximum simultaneously supported QoS users and overall system throughput by non-optimal placement of 6 APs.

Overall, the performance of the DAS and the IDS is quite robust towards a non-optimal placement of APs. The two distinctive placements of APs have nearly no impact on the achieved performance of these two systems. The performance of the

<sup>4</sup>The performance results of the equal-share scheduler with 2-by-2 MIMO is presented in C.1

<sup>5</sup>The performance results of the QG scheduler with 1-by-2 SIMO are presented in C.2.

plain Femto system with a QG scheduler can be deteriorated by the non-optimal AP placement by 5% to 15%, but still outperforms the DAS. The performance of the Femto HFR 2 is quite sensitive to AP placement. Both its supported user number and system throughput are quite unstable in the two scenarios. Up to 30% and 20% of loss in the two KPIs, respectively, can be seen, which makes the Femto HFR 2 system perform even worse than the plain Femto system. The Femto FFR and DR system show smaller degrees of sensitivity to non-optimal AP placement. A positive gain is maintained on the supported user number compared to the plain Femto system.

By analyzing the above result, we strongly recommend the use of the QG scheduler in a densely deployed multi-cell indoor network, when heavy traffic load is congesting the network. By using centralized coordinated scheduling, the IDS can provide the best user experience on high data speed applications and at the same time support the most number of users. However, currently there is no available product that implements similar multi-cell scheduling concept. The Femto system is more likely a competitive indoor solution to the DAS. The performance of the Femto system beats the DAS in both supported user number and system throughput with a 2-by-2 MIMO configuration by using a QG scheduler. The Femto HFR 2 can further improve the Femto system performance in the highly interfered scenario. However, its gain is subject to a good radio planning of the system and is likely to perform even worse than the plain Femto system in a non-optimal placement scenario. The FFR and DR are two alternative schemes to help support more users in the Femto system, whose performance is relatively more robust than HFR 2 towards a non-optimal placement of APs. The Femto DR system offers the user a stream-like service, where all users receive almost the same downlink data rate. A summary of the performance of the investigated variant indoor systems with the QG scheduler is illustrated in Figure 3.16.

The discussion and conclusions drawn from the result with the QG scheduler are further verified by simulations utilizing a general office building model. The two sets of results agree in major conclusions comparing the different indoor systems. The result with the general office building model can be read in Appendix C.3.

### 3.4 Uplink Performance with Selected Power Control Scheme

In our performance evaluation, our focus is mainly dedicated to the downlink where the majority of data traffic is generated. However, the performance of the uplink should not be neglected. Because without adequate capacity of the uplink, congestions will first occur in the uplink which will in turn slow down or even fail the downlink transmission. We include the uplink study to make sure that



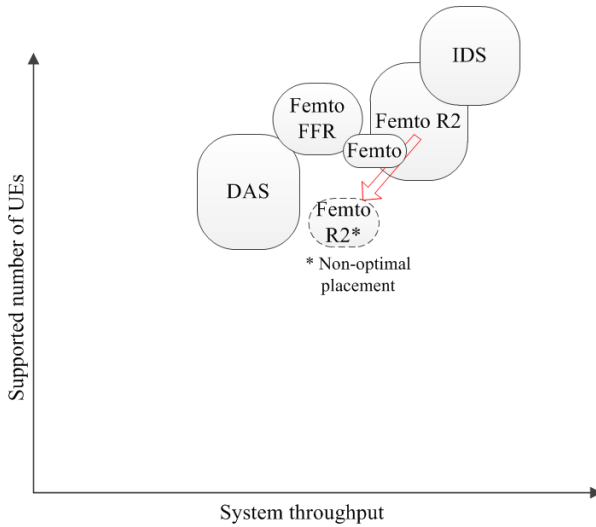


Figure 3.16: Summary of indoor system performance with the QG scheduler.

uplink will not become the bottle neck in the high capacity, high data rate indoor applications.

The performance evaluation is also accomplished by system simulation for the uplink. To boost the uplink capacity, the widely adopted power control scheme, the Fractional Power Control (FPC) is used. The optimum parameter setting for the enterprise in-building deployment is studied and found in our study presented in Appendix D. In the rest of this section, the uplink performance is shown assuming that FPC is applied with the optimum parameter setting. The cumulative distribution of SINR measured at single receiving antenna port is plotted and compared to the downlink in Figure 3.17. In the uplink simulation, the 2-by-2 MIMO configuration and the equal-share scheduler is used. For the multi-cell systems, no frequency reuse or coordinated scheduling is assumed, which means that the uplink operation, and thus the SINR distribution, is identical for the variant Femto systems and the IDS. However, due to the number of users that can be supported by these systems are different in the downlink, it is necessary to distinguish these systems in the uplink performance analysis.

The uplink SINR for the DAS system is even higher than the downlink. This is due to the fact that in the downlink, the transmit power of the base station is divided and shared among all connected users, which results in limited transmit power per PRB. In the uplink, the total power of a single user can be allocated to the few PRBs allocated to this user, leading to high transmit power per PRB. For the multi-cell systems, the FPC can successfully reduce inter-cell interference, so the uplink SINR is better than the downlink at the lower region. However, the

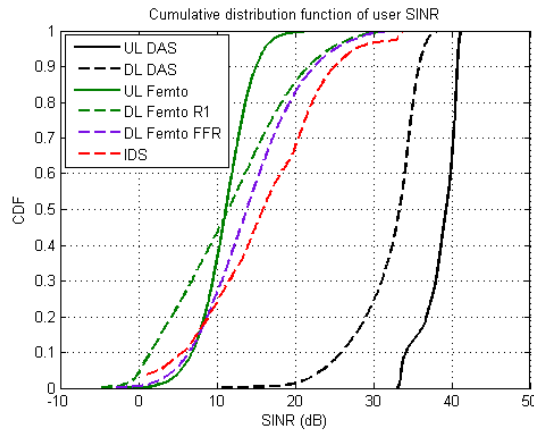


Figure 3.17: Cumulative distribution function of uplink and downlink SINR measured at single receiving antenna port.

FPC also restricts the transmit power of cell-center users, which results in a more concentrated SINR distribution (the deviation of any SINR value from the mean SINR value is only a few dBs). The corresponding user throughput distribution for each system is shown in Figure 3.18 with QG scheduler in downlink and equal-share scheduler in the uplink.

For the different indoor systems, the uplink supports different number of users to match with the downlink. So the throughput curves vary by different systems in Figure 3.18.

In general, with the help of the uplink power control scheme, the uplink actually outperforms the downlink in mean user throughput. For the DAS, the uplink performs even better than the downlink due to a better SINR condition. The 5% outage throughput in the downlink of the plain Femto system (Femto R1) is forced to be 2Mbps by the QG scheduler, which is higher than that of the uplink. However, the uplink offers higher mean user throughput because more spectrum can be allocated to high SINR users with the equal-share scheduler. As to the Femto FFR system, except for the better 5% outage user throughput than the uplink, owing to the QG scheduler, the downlink throughput is otherwise lower than the uplink. This is due to the fact that the downlink has 30% less spectrum resource to schedule than in the uplink. With less sacrificed spectrum resources and better SINR condition, the IDS's downlink achieves similar user throughput as in the uplink.

The 5% outage user throughput and overall system throughput of the uplink of all investigated systems are summarized in Figure 3.19. Those results are normal-

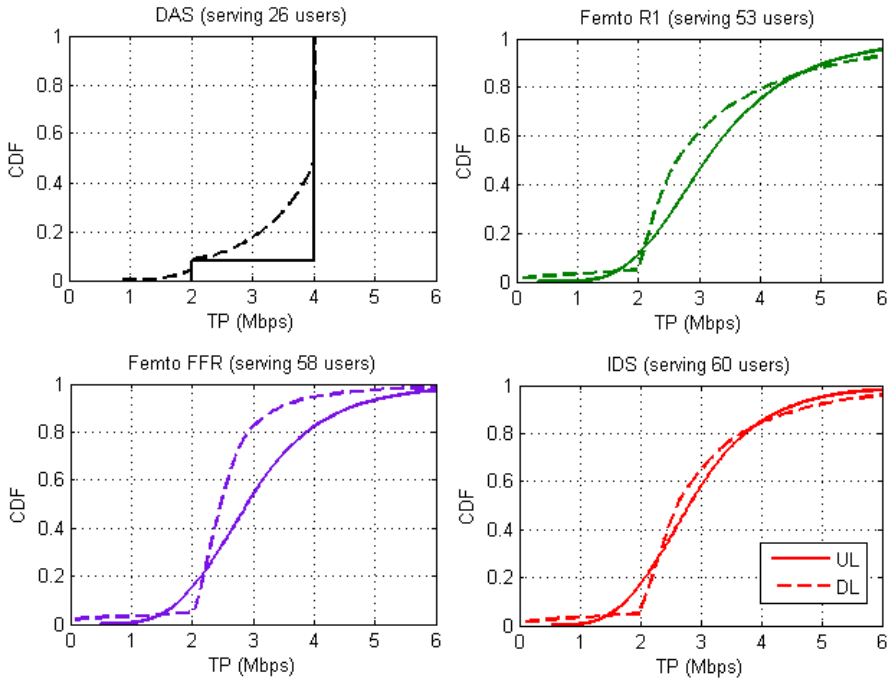


Figure 3.18: Cumulative distribution function of uplink and downlink user average throughput.

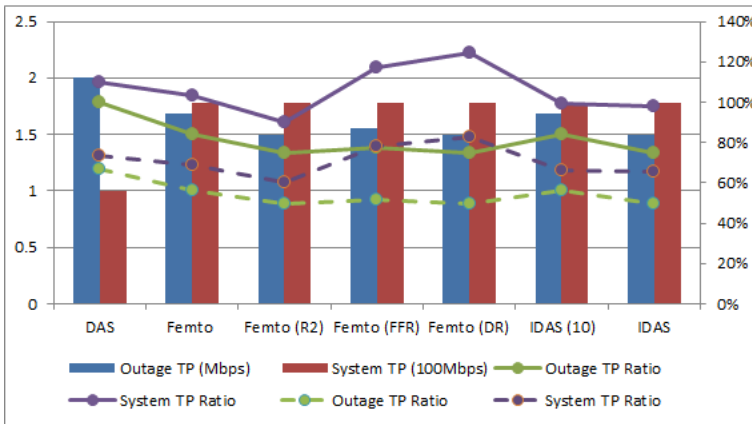


Figure 3.19: Uplink performance of each system and the corresponding ratio comparing to downlink performance.

ized with respect to the corresponding downlink performance, which is shown in percentage in the same figure by solid lines. For example, the outage throughput

ratio is the outage throughput in the uplink divided by the outage throughput in the downlink assuming the number of users supported by the system is maximized in the downlink.

As we can see, the uplink achieves at least 70% that of the downlink in 5% outage user throughput and achieves almost equal or even higher system throughput than in the downlink. We assume in the worse case the dual-stream transmission is not supported in the uplink.<sup>6</sup> The normalized uplink performance with respect to the corresponding downlink performance is shown by the dashed line. The uplink still achieves more than 50% of the performance obtained in the downlink. With such performance, the uplink is not considered to become the bottleneck of the network.

## 3.5 Summary

In this chapter, the capacity of different in-building wireless systems to provide high volume, high-data-rate services is evaluated and compared by system simulation. In the performance analysis, two office building models are used. The results generated from the site-specific model are verified by those obtained from the generalized building model. We get consistent results between these two models.

From the radio performance point of view, single cell DAS is not suitable for in-building high-data-rate services, because its capacity is restricted by the single-cell peak data rate. Even though it outperforms Femto system on supported user number at low AP number in the 1-by-2 SIMO case, the Femto system achieves higher overall throughput than DAS, and the loss in supported user number can be overcome by the use of the quality-guaranteed scheduler. The proposed centralized coordinated scheduling system, IDS, gives the best performance among all investigated systems in all simulated scenarios.

In the worst case scenarios, i.e. with full load traffic, high performance of Femto system can be expected using HFR 2, at the cost of radio planning for good AP placement or through other interference management schemes such as soft frequency reuse (FFR and DR). Besides providing additional gain, the soft frequency reuse scheme is proven to be able to help improve the system stability in case of a sub-optimal AP placement. While the application of the IDS is restricted by the availability of implementation in products, the FFR and DR schemes are easy to implement in the modern base stations which need no change in the network architecture.

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<sup>6</sup>As uplink dual-stream transmission is not supported by current LTE version (in release 10 and below versions of 3GPP standard). We assume here that the 2-by-2 MIMO performance with dual stream transmission performs 50% better than 2-by-2 MIMO without dual stream transmission.

In a densely deployed multi-cell indoor networks, when heavy traffic load is congesting the network, the use of the QG scheduler is highly recommended. By using the QG scheduler, the indoor system benefits from great improvement on supported user numbers while the loss in the overall system throughput is marginal.

# System Performance with Finite Buffer Traffic

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## 4.1 Introduction

In the previous chapter we have studied several dedicated in-building systems including the DAS, femtocell, and our proposed centralized coordinated scheduling system (IDS), as the enterprise solutions to meet the high indoor capacity demand in the upcoming years. The evaluation was carried out in the LTE context with full buffer traffic. By using a full buffer traffic model, we assume that all distributed network elements are actively transmitting continuously in their entire allocated frequency band, which leads to maximum interference towards all users at all time. This phenomenon is expected to harm especially the plain Femto system with universal frequency reuse, because strong neighbor cell interference is unavoidable. This results in the worst-case estimation of the performance of the plain Femto system, and may lead to biased conclusions on the relative performance of the different in-building solutions in the light of a medium load situation.

In this chapter we use a bursty traffic model with fixed buffer size and Poisson arrival. With such a model, users arrive at and depart from the system according to a certain arrival rate and buffer size, respectively, making the load in the network more dynamic. As a consequence, this frees some of the users from neighbor cell interference and is expected to promote the Femto system for better performance at lower load. This chapter can be regarded as an extension to the previous one,

trying to clarify how the more dynamic interference condition brought about by the finite buffer traffic model will impact the performance comparison. In the previous chapter, we concluded that in most cases, the Femto system with frequency reuse 2 outperform that with reuse 1 especially on the number of supported QoS users. However, the good performance comes with strict requirement on careful radio planning and good AP placement. Similar conclusions are found in other works with residential Femto deployments [7, 8]. In this chapter, a load-dependent performance comparison between hard frequency reuse 1, reuse 2 as well as between the IDS and the Femto system will be made. The high load case corresponds to the full buffer traffic model.

## 4.2 Theoretical Analysis of Femtocell with Fractional Interference

This section provides a simple theoretical analysis of the impact of finite buffer traffic model on the femtocell performance. DAS is a single-cell system without inter-cell interference, and therefore does not benefit from interference reduction when the cell operates at low load.

It has been shown in the previous chapter that a high frequency reuse factor increases the achievable throughput for cell edge users at the cost of poorer performance for cell center users. In the case of full buffer traffic and hence full inter-cell interference, we focus on a user that achieves identical performance with a frequency reuse factor of 1 and 2. Let  $\gamma_1$  and  $\gamma_2$  denote the time averaged SINR with frequency reuse 1 and 2, respectively, and the following equality will hold true:

$$\begin{aligned} TP_{1,full} &= W \log_2(1 + \gamma_1) \\ TP_{2,full} &= W \log_2(1 + \gamma_2)/2 \\ TP_{1,full} &= TP_{2,full} \end{aligned} \quad (4.1)$$

where  $W$  is the available spectrum per user.

With finite buffer traffic, assume that if the system is loaded only half of the time due to the low arrival rate, ignoring the low macro-layer interference and thermal noise, both  $\gamma_1$  and  $\gamma_2$  will increase by roughly a factor of 2 (on average). The achievable throughputs with frequency reuse factors 1 and 2, respectively, then become:  $TP_{1,fractional} = W \log_2(1 + 2\gamma_1)$  and  $TP_{2,fractional} = W \log_2(1 + 2\gamma_2)/2$ . According to Eq 4.1 we have:

$$\begin{aligned} TP_{1,fractional} - TP_{2,fractional} &= W \log_2(1 + 2\gamma_1) - W \log_2(1 + 2\gamma_2)/2 \\ &= W/2 \cdot \log_2 \frac{(1 + 2\gamma_1)^2}{1 + 2\gamma_2} = W/2 \cdot \log_2 \left( 1 + \frac{2\gamma_1^2}{1 + 4\gamma_1 + 2\gamma_1^2} \right) > 0 \end{aligned} \quad (4.2)$$

Eq 4.2 can be interpreted as: the fractional inter-cell interference increases the overall SINR condition with frequency reuse-1, therefore, makes it harder for a higher reuse factor to be beneficial. In fact, the lower capacity of high frequency reuse factor will increase the system load and in turn the inter-cell interference, thus further reduces the performance of high frequency reuse.

Based on the simple analysis we can see that the finite buffer traffic and hence fractional inter-cell interference will have an impact on the performance of femto frequency reuse. While the previously obtained results and conclusions are valid for the high load case, the benefit of a higher frequency reuse factor will reduce in the light load scenario. In the remainder of this chapter, we will rely on extensive simulations to quantify this impact, as well as to study the relative performance between the different in-building solutions in different load conditions.

## 4.3 Simulation Results with Finite Buffer Traffic

In this section the performance of different in-building wireless solutions is evaluated and compared using the finite buffer traffic model. A fixed buffer size is assumed for all users, and different network load is achieved by tuning the Poisson arrival rate. The offered load, which is the product of the buffer size and the arrival rate, is used as a quantitative measure of how much traffic demand the network should support. Depending on the individual capacity of each solution, the same offered load may cause a different number of active users in the system. In case the offered load is higher than what the system can support, the users will pile up and lead to a huge number of users jammed in the system.

Other than the number of active users, which describes how loaded the network is, we also use the cell edge throughput and the average overall system throughput (capacity) as the performance indicators. The simulation assumptions used in this chapter are described in detail in the Appendix B.3 and the finite buffer traffic model following the poisson arriving process is described in Appendix B.3.3. The equal-share scheduler is assumed.

### 4.3.1 SINR Distribution for Different Solutions

The worst case of inter-cell interference for each system is highlighted by the user SINR distribution with full buffer traffic presented in Figure 4.1 (the same figure as Figure 3.6). As can be seen from the figure, the highest downlink SINR is achieved with the single-cell DAS. This is expected because there is no inter-cell interference with the DAS, and the macro interference is relatively low after penetrating into the building. The Femto system has the worst SINR distribution, because of



full inter-Femto interference from all APs. The IDS has a SINR condition much improved over Femto system at the lower range due to the inter-AP interference avoidance by the blocking operation.

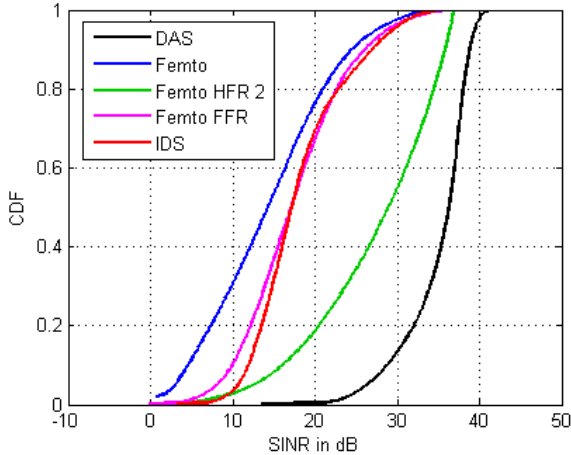


Figure 4.1: SINR distribution of different in-building wireless solutions with 6 APs and full load.

Although beneficial in terms of SINR, the DAS may not achieve as high performance as the other two solutions due to the low effective bandwidth per AP, which leads to low effective bandwidth per user. The plain Femto system (with HFR 1) has the highest bandwidth utilization efficiency. However, it may not achieve the best performance due to poor SINR distribution. By using a higher frequency reuse factor of 2, the inter-Femto interference can be significantly reduced, leading to a significant improvement in SINR. In the case with strong inter-Femto interference and hence poor SINR with HFR 1, the HFR 2 scheme can compromise between the high bandwidth utilization efficiency (the plain Femto system) and high SINR (the DAS) to achieve a better performance than the two systems.

Figure 4.1 also shows that the Femto system with HFR 2 increases the SINR for all users compared to the plain Femto system. While the cell edge users with low SINR will significantly benefit from this, the gain for cell center users with high SINR is only marginal. Considering this, the proposed IDS solution is expected to achieve the best performance as it retains a high bandwidth utilization efficiency while offering enough protection to inter-cell interference. This is evident from the SINR distribution, which is similar to the Femto HFR 2 for low SINR users, but unlike the Femto HFR 2 the SINR does not go unnecessarily high for users in the cell center.

In the following text, we first take a look at the cell-edge user throughput in the next section for the different solutions. The overall system throughput will be

presented later.

### 4.3.2 Cell-Edge Performance

The performance of cell-edge user throughput<sup>1</sup> is a combined effect of both user SINR distribution and per user effective resource occupation, the former of which is subject to number of APs, placement of APs and cell structures. We first take a look at the performance by each individual system, then compare the performance of the different systems in the next section.

The performance of the DAS is shown in Figure 4.2 with different arrival rates and different number of APs. The cell-edge performance of the DAS decreases as the offered load increases. The decrease of cell-edge performance is due to the fact that more and more users share the same amount of resources, as arrival rate and offered load increases. For very high arrival rate that the system cannot accommodate, the arrived users will accumulate in the system, leading to very few resources available per users. As a consequence, the cell-edge user throughput will decrease to zero. This is the situation that may be improved by network planning: depending on the expected traffic demand, the least number of APs should be decided such that the network would be capable of meeting the demand. More access points may be deployed to further increase the per user experienced throughput.

Looking at the performance with different number of APs, we notice that when the user arrival rate is low, one AP is enough to achieve good performance. However, as the arrival rate increases, the gain by increasing the number of APs becomes clear. The performance saturates when the number of APs is high enough to achieve very good SNR within the coverage area of the building (in this case, 3 APs), beyond which the system cannot benefit by having more APs. The performance of the DAS with a non-optimal placement was also plotted in the figure (represented by the dashed line). The result shows that the non-optimal placement has hardly any impact on cell edge performance with high density deployment of the APs.

The performance of the Femto system is shown in Figure 4.3 for both the plain Femto system (Figure 4.3(a)) and the Femto system with HFR 2 (Figure 4.3(b))<sup>2</sup>. Similar to the DAS, the performance decreases with the arrival rate. Between the two Femto systems, it is noticed that the plain Femto system, or the Femto system with HFR 1, is beneficial when the system is lightly loaded (below 40 Mbps). It is because in this case, in most of the time the Femto APs are not simultaneously transmitting, thus the inter-Femto interference is low on average. The plain Femto system benefits from more available spectrum resource per AP. At high load, all Femto APs are actively transmitting, and generates interference to its neighbor

<sup>1</sup>By cell-edge user throughput, we mean the 5% outage user throughput.

<sup>2</sup>When reading these two figures, note that they have different scales on the y-axis.

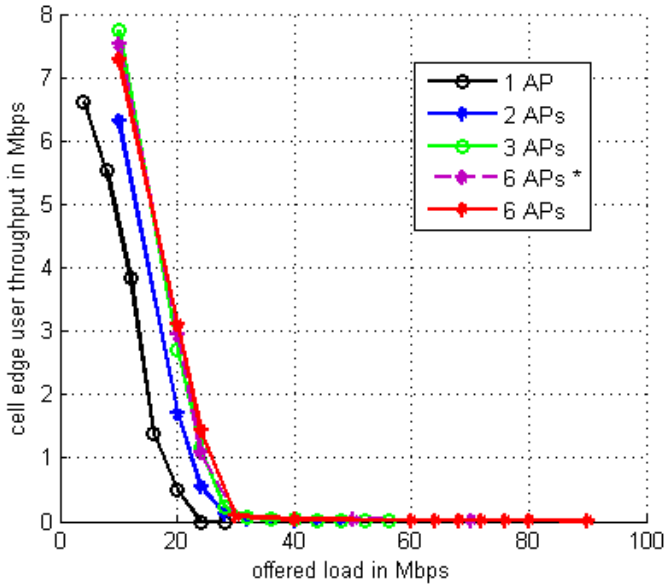


Figure 4.2: SC-DAS: cell-edge (5 percent) user throughput with different arrival rates and number of APs. (\* non-optimal placement).

cells. This is the time when the Femto HFR 2 system performs better. However, the gain provided by HFR 2 in high load is small compared with that by the plain Femto system in light load: for example, when the load is 40 Mbps the cell-edge throughput of the plain Femto system is 20% better than that of the HFR 2 system; with traffic load down to 30 Mbps, the plain Femto system achieves almost doubled cell-edge throughput over the HFR 2 system. It is also seen that a non-optimal placement will deteriorate to a large extent the performance of the HFR 2 system, but not for the plain Femto system.

By increasing the number of Femto APs, unlike the DAS, the performance of the Femto system experiences a corresponding gain, and is thus able to support much higher load. This is due to the fact that the throughput increases linearly with the number of available spectrum resources (APs), but only logarithmically with the SINR.

For the IDS system, the performance is shown in Figure 4.4. Its performance is similar to that of the Femto system, but does not need frequency partitioning and is less sensitive to AP placement. For the IDS, it is also desirable to have a higher number of APs when the offered load is high, though a few APs can provide good performance at low load. Other than the ease of radio planning, the throughput performance of the IDS is also better than that of the Femto system.

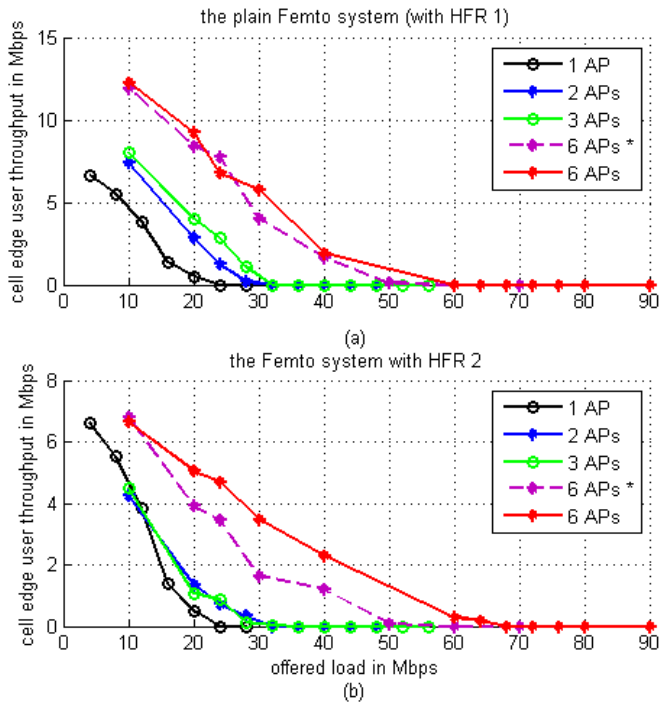


Figure 4.3: Femto cells: cell-edge user throughput with various arrival rates and number of APs. Different frequency reuse factors examined.

This benefit comes from the fact that the IDS can automatically react to the network load condition by only blocking neighboring APs that create significantly high interference. It is therefore better than the Femto system with HFR, where the bandwidth utilization efficiency is pre-defined according to the reuse factor, and unnecessary interference reduction may happen for cell center users whose SINR is already high.

### 4.3.3 Average System Throughput and Comparison between Different Solutions

For each of the considered solutions, their maximum system capacity is compared in this section. For the finite buffer model, the average system throughput is mainly determined by the offered load, and upper-bounded by the maximum system capacity. Their cell-edge performance is plotted again for comparing the different solutions.

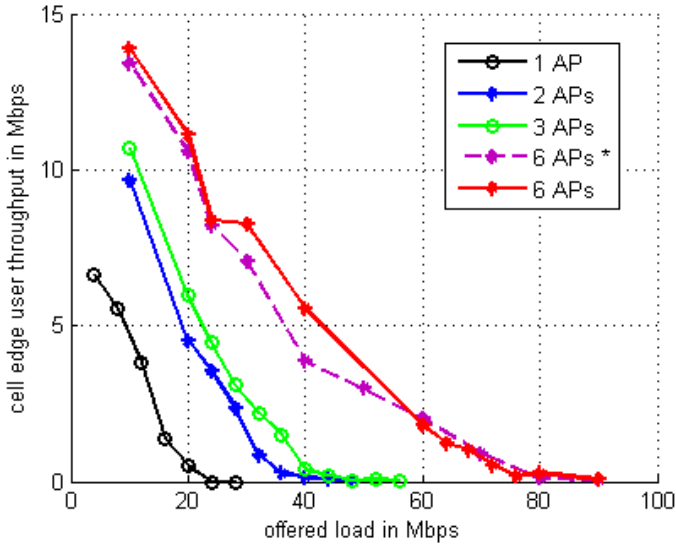


Figure 4.4: IDS: cell-edge (5 percent) user throughput with various arrival rates and number of APs. (\* non-optimal placement)

Figure 4.5 shows the comparison of systems with 6 APs, including a reference line which demonstrates when the capacity meets the offered load. As can be seen from this figure, the system throughput increases linearly with the arrival rate until the maximum system capacity has been reached. When the offered load increases further, the average system throughput remains at that level, but the cell edge user throughput quickly decreases to zero. In this case the users cannot be fully served by the system and will start to accumulate in the system.

As can be seen from Figure 4.5, the DAS offers the lowest system capacity, and for the same arrival rate, it has the lowest cell-edge user throughput among all the solutions due to its low bandwidth utilization efficiency. The Femto system achieves better performance than the DAS, with the HFR 1 being beneficial at low load, the HFR 2 is more preferable at high load. The best performance is achieved by using the IDS, which is better than the Femto system with any frequency reuse configuration.

We make a summary of the maximum system capacity supported by each system with different numbers of APs in Figure 4.6. The advantage of the IDS can be clearly seen from the figure: it achieves the highest capacity for any given number of APs. The performance of the DAS is limited by single-cell peak data rate. Its capacity can hardly be improved by having more than 3 APs in the studied office building. Femto system with HFR 2 can potentially offer improved performance

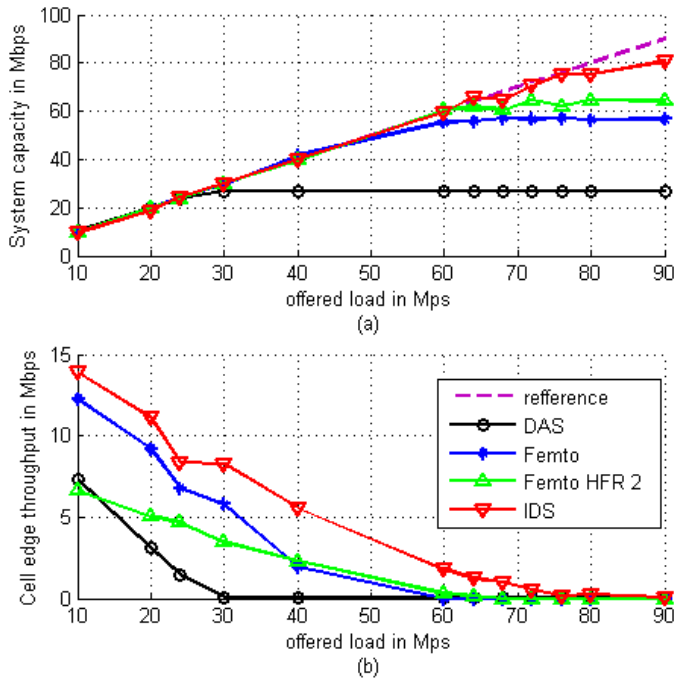


Figure 4.5: System capacity and cell-edge performance of various systems with 6 APs.

compared to the plain Femto system when many APs are deployed, in which case the plain Femto system may suffer from severe inter-Femto interference. The network planning for the IDS and the DAS is easier to be carried out, as these two systems are robust towards a non-optimal placement of APs. It is much more complicated for the Femto system, where a good performance is subject to a proper selection of reuse factor, which depends on the traffic demand and the density of Femto APs; and is subject to a good placement of APs.

The instantaneous number of users in a system versus the simulation time is shown in Figure 4.7, where the arrival rate is 20 users per second (equivalent to 40 Mbit offered load per second) and 6 APs are deployed for each system. The advantage of the IDS can be witnessed as it has an average of 3.3 users per TTI, while there are on average 6.6 users per TTI in the plain Femto system. This indicates that a user served by IDS is able to use more bandwidth resources to achieve high data rate. The high number of users in the DAS system is due to the lack of adequate capacity to serve arriving users. The continuous arriving users become accumulated in the system. In this situation, the user throughput will finally decrease to 0, and a high blocking ratio will be experienced.

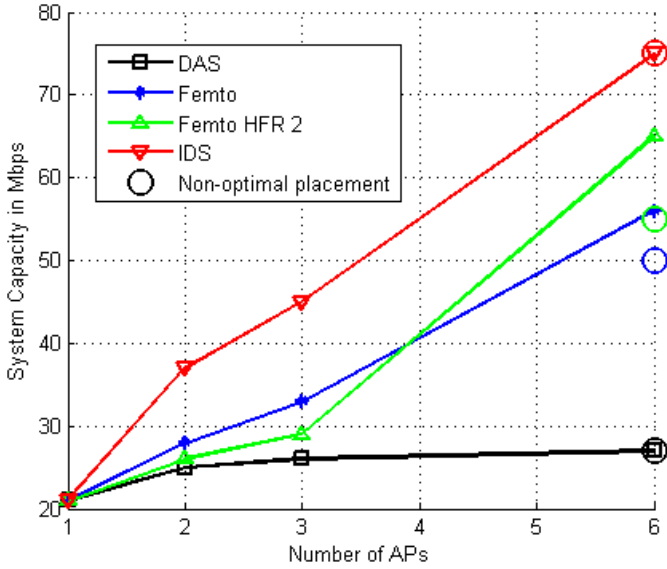


Figure 4.6: Maximum system capacity that can be supported by different systems with different numbers of APs.

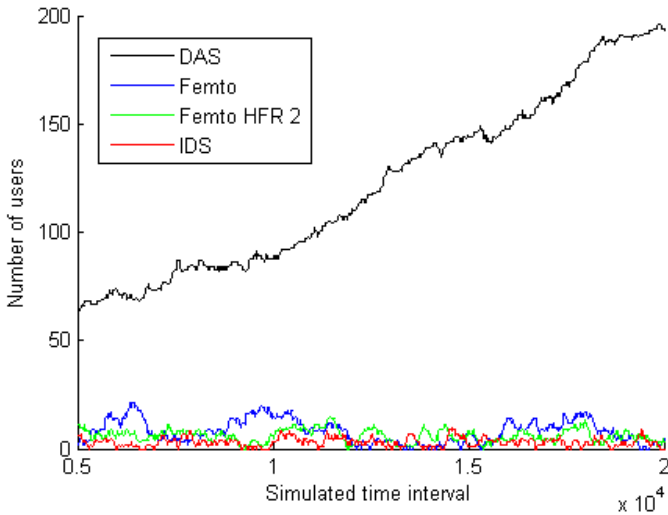


Figure 4.7: Number-of-user variation during simulated time (a warm-up time of 5000 TTI is excluded from figure).

## 4.4 Summary

In this chapter, we extend the previous performance study of different in-building wireless solutions by using a finite buffer traffic model with Poisson arrival process.

Based on the obtained results, it is observed that with both full and finite buffer traffic models, the proposed IDS achieves the best performance. In fact, the gain achieved by the IDS over the Femto system is even more obvious in the finite buffer case with low network load. The IDS achieves almost doubled cell-edge performance than the Femto system with medium traffic load. Other than providing higher throughput, the IDS also benefits in terms of the ease of radio planning: its performance is robust towards a non-optimal AP placement.

The superior performance of high HFR factor of a multi-Femto system is dependent on the network load. When the network is heavily loaded due to high traffic demand, all the APs are actively transmitting, and this is similar to the study made in the previous chapter assuming the full buffer traffic. In this scenario, a high reuse factor of 2 can efficiently reduce the inter-Femto interference and outperforms the plain Femto system with a reuse factor of 1. It is worth noting that the advantage of using HFR 2 is subject to a proper network planning. With a light-to-medium traffic load, the best performance is actually achieved by the plain Femto system. The reason is that with dynamic traffic load, chances are that only part of the Femto APs are active at the same time. Users in a plain Femto system enjoy dynamic interference reduction from neighboring APs. At the same time, the benefit of HFR 2 on improved user SINR cannot outbalance the deficiency of having its available spectrum resource halved. Combined with the conclusions from the previous chapter, the use of HFR, and other partial frequency reuse schemes is not always beneficial to the Femto system which depends on the traffic load. It is suggested the best solution is that the Femto system is able to switch between the reuse 1 and other reuse configurations according to the experienced network data traffic load.

Regarding the poor performance given by the DAS, the deployment of multi-cell DAS instead of single-cell DAS may be a potential solution to improve the DAS performance. In the multi-cell DAS the spectrum resource could be reused spatially, but increased interference raise between APs belong to different cells. The performance of multi-cell DAS is not shown in this chapter but is presented in the analysis in Chapter 5.





# Financial Economical Analysis

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## 5.1 Introduction

The rapid growth of mobile data traffic, along with the fact that the majority of traffic is generated in-building [165] has stressed mobile operators to carefully consider their deployment strategy for in-building capacity and coverage. Though research and discussions regarding the indoor applications of DAS and Femto have been active for years, most mobile operators still hold a quite open view when it comes to a wide-spread deployment of in-building systems for data offloading in their next generation networks with LTE. The essential considerations arise from technical, financial, marketing aspects and also regulatory factors. When investigating the business case of a new product or future technology, it is vital to evaluate not only the technical performance, but also the economic risks and benefits. It is the same when designing network evolution strategies, that technology roadmaps and visions should be supported by economic reasoning.

As small cell solutions for efficient in-building wireless services, the distributed antenna system and Femtocells constitute two major options. Their radio performance has been examined in previous chapters; and in this chapter, we add on top TCO analysis in order to reach technology economical conclusions regarding the scope of applicability of these deployment options for the operator.

In previous chapters the radio performance aspects of indoor wireless systems is

addressed. From a capacity perspective, Femto is seen as a more scalable solution with the potential of serving high traffic demand with dense deployment, while DAS is less scalable than Femto due to faster cost rise as more cells are added. Regarding coverage and mobility performance, Femto relies on effective cell selection mechanisms, which requires more careful planning and optimization; however, DAS is easier to deploy with high coverage and mobility performance. DAS also has some inherent advantages in terms of operability and maintenance allowing the digital and RF components to be located in a convenient location. In this chapter we focus on the financial economic aspect of the indoor wireless solution: TCO. The TCO analysis is expected to assist the indoor performance study to produce an integrated indoor solution road map; to find financial economical solutions for indoor wireless deployment that feed the high indoor capacity need and provide ubiquitous indoor coverage. The result will help us obtain a better understanding of the future cost-efficient indoor solutions depending on different application scenarios. We conduct the TCO analysis for indoor DAS and Femto systems as incremental network deployment for enhanced high-speed data service using LTE technology.

Some other studies can be found on similar topics, for example in [166]. However, their works focus on the mobile operators' massive network rollout with incremental indoor small cells and analyze the cost savings compared to macro-only upgrade. In some other works in [167, 168], the authors try to "quantify the cost effectiveness of such heterogeneous networks and an evaluation of cost effective capacity expansion strategies for urban areas. In general, financial considerations for operators include cost drivers, as well as willingness to take risks, and availability (and cost) of capital." They explicitly include the annual revenue expectations in their calculation. The conclusions are made to enable mobile operators to get a rough estimation of their future profit margin. However, in our study we assume that the need for a dedicated in-building wireless solution is mandatory. Our focus has been put on comparing the effectiveness of the two indoor wireless solutions. We assume that for the same traffic need and QoS service provided, the income from service provision is fixed, the economical benefit comes from the cost saving by selecting the more suitable indoor solution. In this way, the expected future revenue is excluded in our calculation.

We now take a look at the detailed cost structure of an indoor wireless solution. Normally a mobile operator's cash investment includes the cost of network infrastructure, value added service, operation and support systems, marketing and sales etc. In our study the signaling protocols, service delivery platforms, marketing, and administrative costs are omitted, because those costs are highly case dependent and are hard to model or quantify. Furthermore, they are, to a large extent, independent of the radio access technology or architecture used. In this study it is more important to compare the alternative indoor solutions and their opportunities in variant scenarios than just provide all sets of cost figures that do not differentiate for both solutions. In this context, we will focus on the distinc-

tive cost structures for DAS and Femto solutions. We assume that for the same mobile operator costs that are not related to network infrastructure are of the same amount regardless of the indoor solution we use. The main cost difference occurs in the cost of construction and maintenance of the network infrastructure. An example of network infrastructure architecture using LTE technology is shown below in Figure 5.1:

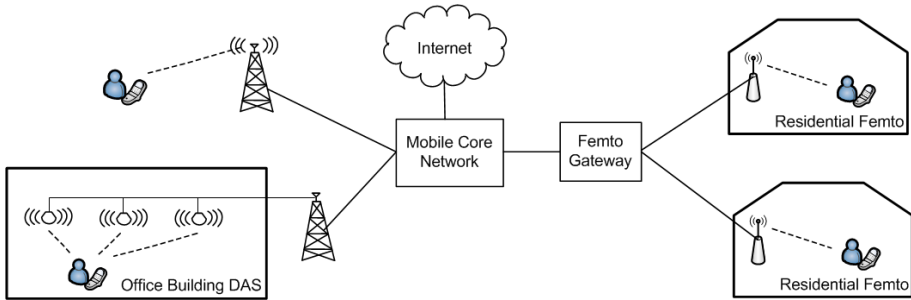


Figure 5.1: Overview of the Mobile Network Infrastructure.

In the middle of the figure the mobile core network is seated, which also includes different layers of access rings by different levels of inter-connected switches or routers. The LTE base stations or LTE eNodeBs are connected to the mobile operator’s core network by connecting to the nearest switch via dedicated high speed link. The Femtocells use a different approach to connect to the core network. The FAPs connect to the mobile core network by connecting to a Femto gateway (a Femto gateway can support up to thousands of individual Femtocells) via DSL or other broadband wired lines. The Femto gateway performs routing, among other things, and thus hides the identity of the FAPs from the core network. In our study core network costs including the access rings are intentionally omitted, since these costs are largely independent of the radio access technology and architecture used. So the cost analysis of an LTE eNodeB fed distributed antenna system is conducted taking into account the indoor distributed antenna system, the eNodeB and the ‘last-mile’ backhaul to the nearest switch point (the parts to the left of ‘Mobile Core Network’ in Figure 5.1). By the term backhaul, we mean the transport connection from the service provider’s network to the access node of the building. For Femto systems, the cost analysis will take the Femtocells, the Femto gateway, and the connection from FAPs to the Femto gateway into account.

### 5.1.1 TCO Analysis Assumptions

For a specific in-building mobile traffic and QoS requirement, according to the current in-building wireless network status, the indoor TCO analysis will provide

cost information on qualified solutions that meet the mobile service need. In the analysis we focus on incremental indoor LTE evolution such that a site-specific LTE-enhanced indoor system is to be installed in a building site. It is intended for a 2G-and-3G matured operator network, whose indoor 2G and 3G solution is well constructed and fulfills 2G and 3G coverage requirement, and for those who want to upgrade their network to the upcoming LTE generation and seek cost-economic LTE indoor solutions.

The cost figures are strongly dependent on the details of a specific use case, including both technical and market related factors. Hence, to generalize quantitative results, market conditions should be taken great care of when conducting the analysis. For example the product price can be affected by factors which are related to the volume of products sold in certain areas; implementation and operational cost are highly impacted by regional factors such as labor costs; backhaul is another cost component that varies by different solutions, different operators, availability conditions of existing connection infrastructures and is subject to local regulations etc. We based our TCO calculation on average European market prices which are averaged over values collected from variant resources and studies. Due to the fact that the cost figures used in this work are derived from the European market and a similar market like the United States, the result reveals better the European and US business case rather than regions that have quite distinctive cost characteristics. We also study and present a distinctive set of results using prices deprived from the Chinese market as an example to show how geographical factors affect the TCO.

### 5.1.2 Other Considerations Comparing DAS and Femto

Besides performance and cost, there are other considerations that will affect a specific in-building wireless solution. One thing that we have also taken into consideration in our TCO analysis is the problem of different QoS prioritization on transport. From this aspect, DAS is deployed on dedicated front-haul (link from radio source to remote radio amplifier), so all traffic is prioritized within the system. However, if we want to take the benefit of Femto to re-use existing Ethernet infrastructure for intra-building transport, QoS prioritization requires special configurations as "Femto service" is not a standard prioritization class on the best effort Ethernet<sup>1</sup>. We address this problem by adding an additional cost on a per-Femto basis in order to facilitate in the Femto systems the same QoS

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<sup>1</sup>Detailed discussions about QoS provisioning for Femtocell integrated networks can be found in Chapter 2. The QoS problem of Femtocells is addressed in [141, 169–171]. Solutions to guarantee QoS for Femto systems in a Internet Service Provider (ISP)'s network are proposed and given in [141, 169, 170]. When wireless and wireline operators are separate entities, a certain Service Level Agreement (SLA) has to be set up, or the Femtocell has to be equipped with opportunistic QoS solutions. In either case, advanced feature upgrade is required in FAP or in the ISP network intermediate nodes or in both of them.

guaranty as offered by the DAS using dedicated transport.

There are many other advantages and disadvantages for both systems, which are hard to quantize by a single monetary value, such as the ease of installation of Femto systems versus the work-disruptive and time-consuming installation of DAS front-haul; more frequent, sometimes difficult maintenance site visits (due to restricted access in many office buildings) of multiple Femto cells versus centralized maintenance of DAS where the base station is located; as well as the appealing multi-operator, multi-technology feature of DAS<sup>2</sup>. These are all factors the investor should take into consideration when making a decision on a specific in-building wireless project. We should be aware that performance and cost alone will not determine a specific in-building deployment. However, a quantified performance and cost analysis helps to have a clearer vision on the potentials of different in-building systems and thus is valuable and influential on the rollout of future networks.

## 5.2 TCO Modeling and Methodology

In this section we will discuss the major components of the total cost of ownership, with a focus on the LTE enhancement of indoor solutions. We discuss the unique cost features of DAS and Femto systems and highlight the importance of backhaul visibility in the cost analysis.

The Total Cost of Ownership is a financial estimate to determine the direct and indirect costs of a product or a system over a certain time period, which is composed of CAPEX, Implementation Expenditure (IMPEX) and OPEX, see [172], page 57-58 in [173].

$$TCO = CAPEX + IMPEX + OPEX \quad (5.1)$$

The concepts of CAPEX, IMPEX and OPEX and their applications in indoor wireless systems are discussed in this section, followed by a brief introduction of the discrete present value method used in the TCO analysis. A summary of categorized detailed cost elements of DAS and Femto can be found in TABLE 5.1.

### 5.2.1 Capital Expenditure (CAPEX)

CAPEX, by definition, is incurred when a business spends money either on buying fixed assets or on adding to the value of an existing fixed asset with a useful life that extends beyond the taxable year. CAPEX is spent on assets that can be disassembled and relocated. In the context of mobile operators, CAPEX represents

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<sup>2</sup>Some analysis results can be found in Appendix G.

the initial equipment and software investments that are related to deploying and upgrading the mobile networks.

The newly constructed indoor DAS systems often adopt a “light version” of DAS, where a compact base station can be mounted on the wall instead of occupying a furnished equipment room. The wall mounted base station can either be a small sized Pico indoor base station or a compact base station employing a base band unit plus one or multiple remote radio-frequency units (BBU+RRU). Some product examples of compact base stations can be the Flexi Multiradio BTS produced by Nokia Siemens Networks, ZXG10 SRRP system by ZTE and Huawei’s Distributed Node B series. The BBU, or also called the system module, and the RRU, or radio frequency module, are connected by fiber optic. The RRU can be stretched to locations close to the remote antennas, in which way it shortens the length of coaxial cable deployment and reduces the cable loss in the system. Due to the light weight of the BBU and the RRU, they can both be wall-mounted, or the BBU can also be located and share room with the integrated power cabinets, or in a 2G cabinet. With such a “light version” of DAS, an equipment room and associated supporting equipments are not needed (for existing DAS, since the operator is already paying for the site related costs, there should be no incremental expenditures when adding LTE in the system.). Huawei claims that such architecture can save up to 30% of the TCO on site construction due to relaxed requirement on equipment room and eased installation of base station [174]. In fact, the equipment room alone can reduce the CAPEX by thousands of Euro, by avoiding purchasing cooling system, alarm system, base station rack and other supporting equipment.

The common parts of CAPEX for DAS and Femto are the base stations, i.e. LTE eNodeB or FAP, and the backhaul equipment. For small cells such as Femto cells, the remaining CAPEX is the investment in Femto Gateways and Ethernet router; whereas many small parts should be included in the CAPEX calculation for DAS, e.g. multiple remote antennas, feeders and combiner/splitters.

### 5.2.2 Implementation Expenditure (IMPEX)

IMPEX literally means the implementation expenditures. It is the capital expenditure that would have to be repeated if the cellular site were moved. In most cases, the costs are associated with planning, installing and testing the system.

The IMPEX normally includes the site acquisition cost, the installation cost, the network planning cost, and coordination cost due to disruptive construction work of DAS. For in-building systems, as discussed above, the need for an equipped site location is quite relaxed. As base station equipments can easily be mounted on walls, it is possible that site acquisition and construction is not needed. The

expenditure on installation of the system can be calculated by summing up the cost for installation of each system elements. At last, the network planning and coordination should also be considered. This part of the cost is hard to estimate and varies a lot depending on many factors from labor cost to business type of the building and to the length of the system construction period which will probably disturb the ordinary office work in the building. However, it should be related to the scale of the project, i.e. the indoor coverage area size or the number of remote antennas. In this study we assume that the system planning and coordination cost of the IMPEX is fixed per FAP. For the DAS, it is proportional to the total length of the cable deployed and to the number of remote antennas.

For example, the installation cost of a FAP is assumed to be 150 €, which amounts to about one hour's labor commission; and the designing and planning cost for the Femto system is accordingly assumed to be 150 € per Femto. The above value of IMPEX is valid for the first-time Femto deployment, and will be reduced in other cases. For example, the IMPEX is lower when replacing a Femto, due to the fact that the DSL cable is already available at the Femto location; and no planning effort is needed either.

### 5.2.3 Operational Expenditure (OPEX)

OPEX is the operational expenditure. It is the ongoing cost for running a product, business, or system. In the context of mobile operators, OPEX is related to operation and maintenance of networks and service provisioning. Except for backhaul related OPEX, the remaining part can be estimated as a fixed portion of the total CAPEX. In mobile networks, the yearly OPEX excluding backhaul expenditure is often estimated as 5% to 10% of the total CAPEX. More specifically, it is assumed to be 5% of CAPEX for macro and micro base stations by [175], thus the DAS system; and is 10% to 20% for small cells like Femtocells [167]. The higher bound of 10% and 20% for DAS and Femto system, respectively, is used in this study.

In later sections we will make a separate study on TCO depending on the availability of backhaul. This is due to the fact that the backhaul cost is quite significant and variant, resulting in a large impact on the TCO of in-building systems. The variance of backhaul cost comes from different backhaul solutions, local backhaul availability and some other regional or market reasons. Currently the most widely adopted backhaul solutions are leased E1/T1 lines and microwave link, with leased Ethernet and fiber paving their way and gradually taking a growing share of the market.

The authors in [176] claim that the mobile network operators' annual spending on leased backhaul transmission constitutes up to 40-60 percent of their overall OPEX in 2009. However, we expect that the backhaul cost is declining year by



year. The prices of microwave links have dropped along with their vast adaptation in mobile backhaul transmission. Despite the fact that cost for fiber equipment has decreased considerably in recent years, massive fiber deployment is limited by high cost for digging and local regulations. However, we have seen that fiber is increasingly available in urban areas. It is expected that with the vast deployment of fiber networks, the backhaul cost has great potential to drop faster than the other parts of the network.

Table 5.1: Summation of TCO Components.

	<b>DAS</b>	<b>Femto</b>
<b>CAPEX</b>	Base station Antennas and auxiliaries –remote antennas, wideband combiner, power splitter, coupler, coaxial cable, cable connector, etc. Backhaul equipment Software and license Supporting equipment –wall mounting kit, power cable, battery backup, alarm system, etc.	Base station –antenna/front-haul integrated, software license included in price.
<b>IMPEX</b>	Site acquisition and construction System planning and initial optimization Installation of base stations Installation of distributed system Coordination cost due to disruptive DAS construction work	System planning and initial optimization Installation of base stations
<b>OPEX</b>	Backhaul operations and maintenance Backhaul rent Site rent Power consumption Offsite support Site visit for trouble shooting or maintenance	Backhaul operations and maintenance Backhaul rent Power consumption Offsite support Site visit for trouble shooting or maintenance

### 5.2.4 Discrete Present Value

The Discrete Present Value (DPV) analysis is an important tool in our TCO analysis for evaluating the outgoing cash flow of the project. In the DPV analysis, all discrete future cash flows are estimated and discounted to give their present values. DPV is defined by the following expression [177] (as Net Present Value, NPV, in the referred literature):

$$DPV(VF_1, \dots, VF_N, N, r) = \sum_{t=0}^N \frac{VF_t}{(1+r)^t} \quad (5.2)$$

Where  $VF_t$  stands for the future value at the beginning of the  $(t+1)^{th}$  period ( $t=0$  means that  $VF_0$  is the present value by itself);  $N$  is the total number of periods and  $r$  stands for the discount rate. The discount rate, or the risk adjusted interest rate, accounts for inflation and the time value of money meaning how much the creditors would like to receive the same amount of money now instead of in the future taking the risk of the project into account <sup>3</sup>. In our analysis, we use a simple model that assumes the discount rate to be equal to the annual interest rate.

In the following analysis, unless otherwise stated, the time period is counted in units of year, and the total TCO is calculated for a 5-year period,  $N = 5$ , including the discounted 5 years' OPEX. Assuming that the OPEX for each year is a fixed value (denoted by OPEX'), the calculation of TCO in Eq. (5.2) can be updated to have the form of Eq. (5.3).

$$TCO = CAPEX + IMPEX + OPEX' \cdot \sum_{t=0}^{N-1} \frac{1}{(1+r)^t} \quad (5.3)$$

When the interest rate  $r = 0.05$ , number of years  $N = 5$ , the multiplying factor on the single-year OPEX becomes  $\sum_{t=0}^{N-1} \frac{1}{(1+r)^t} \approx 4.55$ .

## 5.3 Indoor System Design

An office building model is necessary in designing the site-specific in-building systems and in evaluating their radio performance. By extended system simulation, which is analyzed in previous chapters, the offered capacity and performance of each possible solution can be obtained and compared. The building model is shown

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<sup>3</sup>More information and definitions of discrete present value and present value can be found in [166] and [178].

in Figure 5.2, which follows the WINNER II office model [166]. It has three floors of the same floor plan, each floor with two corridors and two rows of office rooms at the side of each corridor.

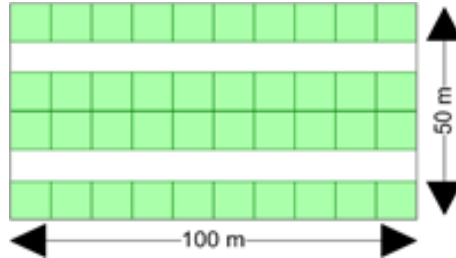


Figure 5.2: Site-specific floor plan.

### 5.3.1 Femto System Design

Femtos are portable, low cost and low range BSs first designated for indoor usage, where they are connected to the operator's network by residential Digital Subscriber Line (DSL) or cable broadband [178]. In the case study with the applied building model, 12 Femtocells<sup>4</sup> are used to cover the whole building (according to coverage performance examined by simulations), amounting to 4 Femtocells per floor and 1250 square meters coverage per Femtocell.

The TCO calculation of Femto systems is more straight forward than DAS due to less cellular equipment involved. Normally, the installers can simply plug in the Femtocells to the nearest Ethernet port. In the worst cases, when FAPs ought to be placed at the predefined locations by careful radio planning, some necessary re-cabling work is required to stretch the DSL cable to the suitable Femtocell locations.

### 5.3.2 DAS System Design

In the discussion in this section, we distinguish between a new DAS installation and the upgrade of an already existing DAS installation.

<sup>4</sup>Unlike DAS, an LTE FAP is always assumed a MIMO device.

## 5.3.2.1 New DAS

DAS is composed of many remote antenna ports distributed over a large area and connected to a single BS by fiber, coax cable or microwave links. Without advanced signal processing at the central BS, the same downlink signal is broadcasted on all its antennas. A DAS system is designed for the studied building, following the guidance in [111], and is illustrated in Figure 5.3. The figure shows only the distributed system design for the middle floor since the same design applies to the other floors.

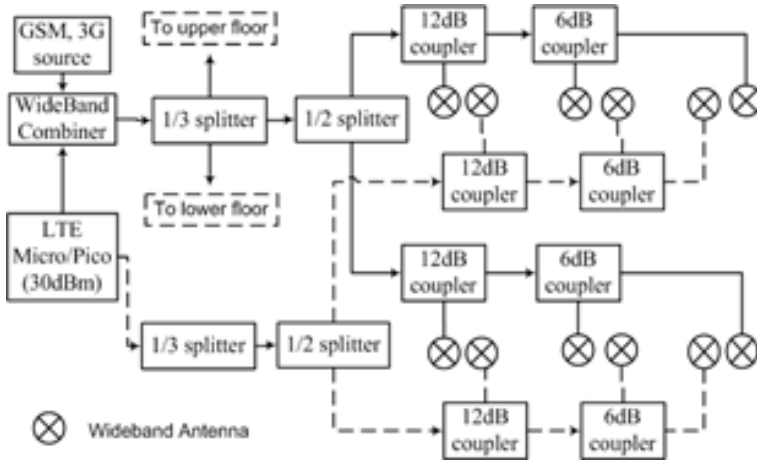


Figure 5.3: Distributed antenna system design.

The devices that are connected with solid lines, along with the cables, implement a single antenna (SISO/SIMO) DAS system, which is normally seen in 2G and 3G networks. In the era of LTE, mobile operators may be willing to build a multiple antenna DAS to achieve higher peak data rates by MIMO technique. This requirement adds installation complexity to the system, because a parallel distributed system is needed [111]. This parallel distributed system is illustrated by the parts that are connected with dashed lines.

In this design illustrated in Figure 5.3, a Micro or Pico LTE base station is used as the signal source, which has output power of 30dBm for 10MHz system. In a single antenna system, 6 distributed antennas are used to achieve full coverage of a single floor. The maximum coverage distance of a single antenna is about 22.5 meters, which is enough to provide above -80dBm downlink receive signal strength even at 12dBm output of antenna, according to [111] (Table 8.6). If the system is fed by a macro base station with output power of 43dBm for 10MHz system, the number of remote antennas can be safely reduced to 4 per floor due to

higher output power at RRU. In this case, the cost figure varies accordingly due to reduced cost for cabling and remote antennas, but raised cost of base stations. Examples of cost can be found in section 5.4.

### 5.3.2.2 Reuse Existing DAS Cabling

Under many circumstances, an existing 2G or 3G DAS is already installed in the building, and higher capacity can be added by simply inserting the LTE base station at the signal source. Referring to Figure 5.3, the installer merely needs to insert the LTE base station as another input of the front end combiner. In most cases, the combiner needs to be replaced by a wider band combiner to be able to accommodate the higher frequency band introduced by the LTE system. We assume that the other passive components can always support the added LTE bandwidth, and that the remote antennas are so well planned that good LTE coverage is achieved, and no replacement of any existing passive device or installation of new remote antennas is required.

For MIMO DAS, as one path of the distributed system can reuse the existing infrastructure, this means that only one path of the distributed system is to be built. An example of such upgrade is illustrated in Figure 5.4 in bold lines (denoted as “tx 2”, where “tx” stands for a transceiver pair) with a system module plus RRH solution <sup>5</sup>. The difference between an RRU and RRH is that the RRH has less capacity and is thus cheaper than the RRU. The RRU is a multi-sector device, where the RRH is a radio frequency module that can support only one sector.

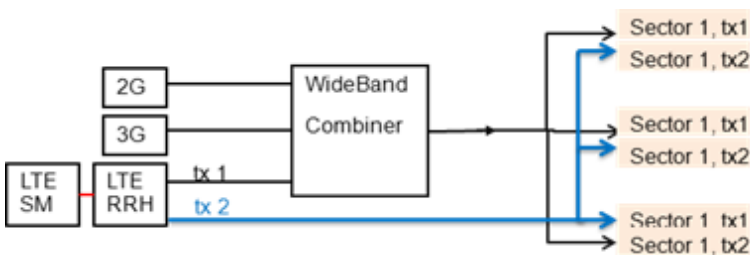


Figure 5.4: Upgrade a single-(colocated)-antenna DAS to dual-(colocated)-antenna DAS.

<sup>5</sup>Here we adopt the Flexi Multiradio BTS product by Nokia Siemens Networks as example. Commercial product introduction is available online at: [http://w3.nokiasiemensnetworks.com/NR/rdonlyres/9DD8041D-DD13-424E-BDA2-6F034787D5D8/0/Flexi\\_multiradio.BTS\\_090202.intranet.pdf](http://w3.nokiasiemensnetworks.com/NR/rdonlyres/9DD8041D-DD13-424E-BDA2-6F034787D5D8/0/Flexi_multiradio.BTS_090202.intranet.pdf), last visited July 2012

### 5.3.2.3 Multi-sector DAS

In the design illustrated in Figure 5.2, the whole building is covered by a single LTE sector. Further capacity can be inserted by splitting the DAS cell into multiple sectors. For example, by introducing two new Micro/Pico base stations or two new RRHs into the system and distributing signal from different sectors on different floors, there will be one sector, or cell, on each floor. An SM plus RRH solution is illustrated in Figure 5.5 for this scenario. The signal from RRH has to be combined

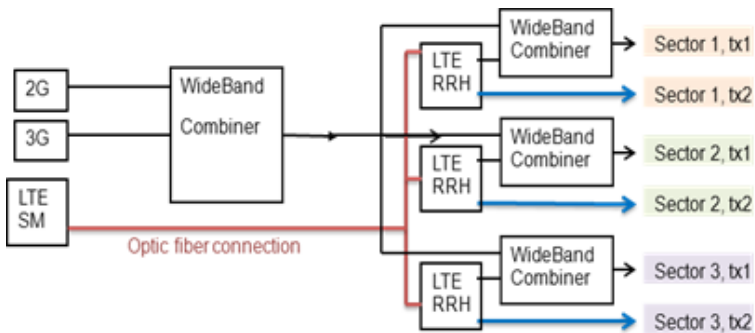


Figure 5.5: Upgrade a single-sector DAS to multi-sector DAS.

with 2G and 3G signal after the latter is power divided for distributing on each floor. Thus new combiners are needed per sector.

## 5.4 Summary of DAS and Femto TCO Features

Both DAS and Femto have their unique cost features, due to their distinctive cost components. We exhibit the TCO features of each of the systems and give detailed cost examples in the following subsections.

### 5.4.1 Femto

As each FAP is a standalone small base station and due to its “plug-and-play” nature, the cost formation of the Femto system is quite straightforward and involves only a few components regarding the hardware, installation and maintenance.

The cost of a FAP is expected to be low and in the range of a few hundred Euro. However, additional cost may incur when stricter QoS or security requirement is imposed. Built-in functionalities to support mobile QoS requirement as well as

enhanced self-organizing features and better security management may be implemented in FAPs or in local network routers (to prioritize specific Femto traffic flow for delay sensitive applications), but in each case at additional cost. An additional cost per Femto is applied in this situation, which contributes to a high-cost Femto. The Femto-related cost figures used in this study are listed below:

- CAPEX Enterprise FAP:
  - Low-cost Femto: 250 €
  - High-cost Femto: 800 €
  - Depreciation period FAP: 2.5 years
- CAPEX Femto gateway and router:
  - 40 € per Femto share
  - Depreciation period Femto gateway: 5 years
- IMPEX Installation and Configuration (per Femto):
  - Low-cost Femto: 150 €
  - High-cost Femto: 250 €
  - Replacement of old Femto: 100-150 €
- IMPEX Radio Planning and Testing (per Femto):
  - Low-cost Femto: 400 €
  - High-cost Femto: 400 €
  - Replacement of old Femto: 0 €
- OPEX Annual Operational and Maintenance cost:
  - 20% of CAPEX

Note that the TCO calculation yields a period of 5 years. Because the FAP depreciation period is only 2.5 years, replacement of FAP will take place during a longer time period. Under such circumstances, the CAPEX and IMPEX of Femtocell in Equation (5.4) should be calculated as discounted present value, taking the replacement after the first 2.5 years into consideration <sup>6</sup>.

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<sup>6</sup>For passive DAS components whose depreciation period is longer than 5 years, described in later sections, their cost will only be partially accounted into the TCO analysis depending on the actual depreciation period.

$$\begin{aligned}
TCO_{Femto} &= CAPEX_{Femto} + \frac{CAPEX_{replace}}{(1+r)^{2.5}} \\
&+ IMPEX_{Femto} + \frac{IMPEX_{replace}}{(1+r)^{2.5}} + OPEX
\end{aligned} \quad (5.4)$$

due to,

$$\begin{aligned}
OPEX &= OPEX_{maintenance} + OPEX_{backhaul} \\
&= 0.2 \cdot CAPEX_{Femto} \cdot \sum_{t=0}^4 \frac{1}{(1+r)^t} + OPEX_{backhaul}
\end{aligned} \quad (5.5)$$

and,

$$CAPEX_{Femto} = CAPEX_{replace} \quad (5.6)$$

Equation (5.4) could be formulated as.

$$\begin{aligned}
TCO_{Femto} &= CAPEX_{Femto} \left( 1 + \frac{1}{(1+r)^{2.5}} + 0.2 \cdot \sum_{t=0}^4 \frac{1}{(1+r)^t} \right) \\
&+ IMPEX_{Femto} + IMPEX_{replace} \cdot \frac{1}{(1+r)^{2.5}} + OPEX_{backhaul} \\
&= 2.8 * CAPEX_{femto} + IMPEX_{Femto} \\
&+ 0.8852 * IMPEX_{replace} + OPEX_{backhaul}
\end{aligned} \quad (5.7)$$

The TCO of a single Femtocell is thus 1421 € and 3120 € excluding backhaul OPEX for low-cost and high-cost FAPs, respectively. The fraction of CAPEX, IMPEX and OPEX (excluding backhaul cost) in Femto system TCO is illustrated in Figure 5.6.

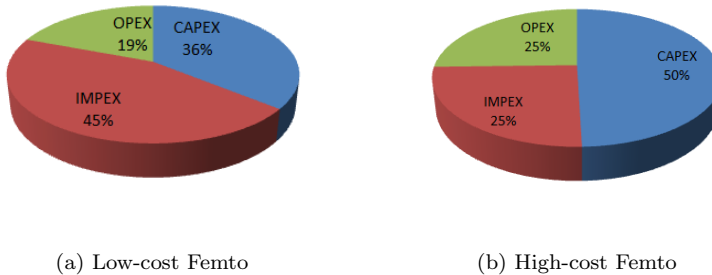


Figure 5.6: Composition of Femto system TCO.



### 5.4.2 DAS

In the TCO analysis of indoor DAS, two base station types are assumed for DAS.

#### •Macro eNodeB

Normally, the Macro eNodeB system module is capable of supporting 3 LTE sectors with MIMO. Based on current European market price, the capital expenditure of a three-sector 2-by-2 MIMO LTE Macro base station including both hardware and software license, is assumed to be 20,000 €. A corresponding SISO configuration costs approximately 15,000 €. When only a single sector is activated in the indoor system, it is assumed that a higher share than one-third of the above price is applied. In our TCO analysis, we take 6667 € and 10,000 € for single sector SISO and MIMO configuration, respectively. The depreciation time of base station equipment is 5 years.

#### •Pico eNodeB

A Pico base station is worth 3,100 €, which supports only a signal LTE sector. If more sectors are required to meet higher capacity need, additional base station equipment and new combiners can be installed. The depreciation time of base station equipment is 5 years.

The list of the other cost components of DAS can be found in Appendix F. The TCO of DAS can be formulated in a similar manner as in the previous subsection, which is presented below:

$$\begin{aligned}
 TCO_{DAS} &= CAPEX_{DAS} + IMPEX_{DAS} + OPEX_{backhaul} + OPEX_{maintenance} \\
 &= \left( CAPEX_{BTS} + \sum_j n_j C_j \right) \times (1 + 0.1 \times 4.55) + \left( IMPEX_{BTS} + \sum_j n_j I_j \right) + OPEX_{backhaul} \\
 &= 1.455 \times \left( CAPEX_{BTS} + \sum_j n_j C_j \right) + \left( IMPEX_{BTS} + \sum_j n_j I_j \right) + OPEX_{backhaul} \quad (5.8)
 \end{aligned}$$

where,  $n_j$  stands for the number of the  $j^{th}$  type of passive devices needed,  $C_j$  stands for the capital expenditure of the  $j^{th}$  passive device, and  $I_j$  is the implementation cost for the device. In Equation (5.8), we assume that the maintenance related OPEX is 10% of the total CAPEX. Compared to Femto systems, the DAS yields lower OPEX. This is due to the fact that multiple Femtocells facilitate more frequent site visit for maintenance or operational purpose, which in turn leads to a higher OPEX proportion compared to CAPEX. In contrast, the fraction is assumed lower for DAS, where the passive distributed system seldom facilitates maintenance effort. The TCO for different DAS configurations is presented in Table 5.2.

Different configurations of DAS lead to quite distinctive total cost values. We summarize some general findings by taking Macro base station supported DAS as an example:

Table 5.2: TCO for Different DAS Configurations Without Backhaul Cost.

System type (price in k€)	Pico BTS as donor BTS		Macro BTS as donor BTS	
	Single-antenna	Dual-antenna	Single-antenna	Dual-antenna
New DAS	19.4	29.3	25	40
Reuse existing DAS	7.35	16	14.5	25.9
Additional cost to upgrade to 3 sectors	16	15.5	22.8	26.8
Additional cost to upgrade to 6 sectors	33.5	35.3	55	70.5

- A single-antenna (SISO) DAS consisting of one LTE sector and 18 remote antennas has a 5-year TCO of around 25,000 €.
- The dual-antenna (MIMO) DAS of one LTE sector and 18 remote antennas has a 5-year TCO of 40,000 Euro, thus 60% more expensive than the SISO DAS system.
- When a DAS already exists, cost savings of 40% for SISO system and 25% for MIMO system can be achieved by reusing one path of the distributed system.
- Adding more sectors into the system is more expensive due to high CAPEX of the base station equipment and corresponding license fee.
- If Pico base stations are used instead of Macro base stations as signal source, the DAS TCO will be lower. In this specific case, the cost of a Pico DAS is on average about 2/3 or less of that of the Macro DAS.

### 5.4.3 Backhaul Solutions

To build a new site the mobile network operators normally need to provide backhaul connection for local traffic to traverse through the operators' transport backbone to the core network. This is done by setting up a connection between the site and the nearest router in the operator's transport access ring. For the Femto system, the router is specifically a local Femto Gateway.

Outside the building a common backhaul solution can be used for either indoor system to connect the external router and the building access node. Inside the building, multiple Femtocells need additional backhaul infrastructure to transport their traffic to the building access node, which ultimately guides this traffic out of the building. It is not a problem for DAS, because DAS has its own dedicated front-haul, which is its distributed system inside the building. Taking advantage

of its IP-based backhaul capacity, Femtocells can directly connect to the existing ubiquitous Ethernet interfaces in the building and share the Ethernet bandwidth free-of-charge (for mobile network operators) with the other applications. We assume that the share of in-building Ethernet backhaul does not incur any additional cost to the Femto system. However, certain QoS guarantee mechanics should be implemented which will increase the cost of the Femto system. We take care of this consideration in our TCO analysis as discussed in the introduction section of this chapter, and the incremental cost is addressed in the high-cost Femto price in the previous subsection. In the later text, we use the term “backhaul” to refer to the outside building backhaul, i.e., the connection from the building to the transport backbone.

The traditional 2G and 3G mobile network uses TDM/ATM-based techniques as transport media for backhaul. The widely used legacy T1/E1 backhaul is optimized for circuit-switched traffic, i.e. voice service. Though for packet-switched data traffic, it is rather inefficient in bandwidth utilization and is costly per MB. Ethernet is an alternative solution to effectively reduce data transport in terms of €/MB, which has another advantage for packet data service as being more scalable in boosting capacity [176, 179, 180]. The application of Ethernet as mobile backhaul was not widely adopted in the early days due to its asynchronous nature and difficulty in management platform [176]. However, many service and equipment providers have claimed that they have successfully solved the problem with their products [179–181]. When data speed exceeds 50Mbps per site, the tendency is to resort to microwave or fiber optic as the transport media [167]. The advantage of microwave and fiber is their very high bandwidth, up to several Gbps and above, and their flexibility in bandwidth extension. Data speed can be increased on the existing fiber optic backbone by marginal additional cost, which involves merely the upgrade of the fiber switches. The additional cost is “almost negligible” [167].

For mobile network operators, from a financial and management point of view, the different backhaul solutions can be categorized into 2 groups: leased line and self owned connectivity. The operators have to pay a monthly lease rate for leased line backhaul, while in the other case they actually own the property of the backhaul infrastructure and have to install and maintain the system on their own.

- Leased line
    - Legacy E1/T1
- The E1/T1 (1.54/2.048 Mbps) circuits are time synchronous, which is tailored to carry real-time traffic like voice and real-time video. It is widely adopted in the GSM era as efficient means of transmitting circuit-switched voice traffic. The early 3G ATM-based data traffic is multiplexed with the 2G TDM traffic and together they transport in such backhaul. However, the E1/T1’s inefficiency in bandwidth utilization is apparent when carrying packet-based traffic, resulting in high

revenue-per-bit for packet data service.

A typical E1/T1 link cost ranging from 200 € to 550 € per month, and ranging from 350 € to 600 € for major European operators in 2008 according to a survey conducted by Tariff Consultancy Ltd.

- o Leased Ethernet-based connectivity

The likelihood that Ethernet will be a promising replacement of E1/T1 resides in the great cost saving it brings about. The Ethernet technique is not originally designed to carry real-time traffic, so for quality guaranteed voice service, it is critical that TDM/ATM emulation over packet functionality is supported. When time synchronization and per-flow QoS is well managed and when the management platform is ready and allows smooth transition from SDH/SONET, Ethernet will become a high capacity low cost replacement for TDM [179]. The mobile network operators can save costs up to 80% by using Ethernet instead of T1, according to a survey conducted by Tariff Consultancy Ltd and [176].

Leased Ethernet service has an average cost of 40 \$ per month per megabit in US [176] and ranges from 30 € to 150 € per month per megabit in Europe.

- Self-owned connectivity

- o Microwave

According to [182], many major European operators are moving towards microwave backhaul either gradually or aggressively to avoid heavy reliance on leased lines. Microwave represents nearly 50% of global backhaul deployments nowadays [183]. It is believed that microwave is less expensive than fiber for most cases except for a very short distance [176, 184].

Potential cost raise of a microwave link lies in spectrum licenses fee and site lease for antenna space. Site lease can be expensive. Fortunately, in most cases, the microwave antenna can share space with roof-top base stations. However, the availability of spectrum can only become more scarce, making spectrum licenses cost go over 2000 \$ in some Western Europe cases [176].

- o Fiber optic

Fiber link has the highest bandwidth among all backhaul media, copper, co-axial, CAT5/6, air (microwave), etc. Its data speed can easily go up to several Gbps. Although both microwave and fiber are inexpensive in upgrading the capacity of existing link, the fiber link depreciates over 20 years while the lifetime of a microwave site is around 8 years. Another advantage of fiber is that once it is deployed, it requires less care than microwave for maintenance, thus lower OPEX.

The weak points of fiber come from the long deployment period, long-term Return-on-Investment and high initial CAPEX hit. Whether Fiber is the optimum backhaul solution depends on its availability. In

areas where fiber is not widely deployed, and long distance fiber lines are to be installed, the digging cost can be significant, especially in regions that have high labor cost. In spite of this, fiber is gradually taking its market in mobile backhauling [184] due to its high capacity and robustness.

Self-deployed fiber has a cost of 35 € to 105 € per meter [176, 184]. In dense urban scenario, the typical cost is around 100 € per meter. Meanwhile, we have witnessed low price leased fiber in the European market at a cost around 400 € per month from Deutsche Telekom [185] and Elisa Finland [186].

## 5.5 TCO Analysis of Indoor Systems

In this section we demonstrate the main findings of the TCO analysis comparing indoor distributed antenna system and enterprise Femto system. The TCO analysis results are intentionally organized into two different scenarios depending on the local service requirement: the first scenario is a capacity-driven, high data-rate offloading scenario, and the second one is a coverage-driven low data service scenario. In the first scenario, the two types of systems are to be compared based on the premise that both of them are able to feed a certain traffic demand as a minimum. Hence, each system has to be carefully designed to ensure that there is enough capacity to support the specific in-building high traffic need. Simulations are conducted to help find the suitable parameters and configurations of system design such as density of distributed antennas and number of sectors/cells needed. In the second scenario, systems are expected to provide basic voice coverage in the indoor area, while the data traffic need is generally low with a very small number of simultaneous users requiring data service. We assume that in the coverage-oriented case the occasional data traffic need can be met by the capacity of a single LTE sector.

To make a clear view on how backhaul cost is impacting the overall picture of TCO comparison, we first show the TCO results without backhaul cost (referred to as pre-BH TCO in the following text) and then present the TCO with backhaul cost in section 5.5.3.

In the first three subsections 5.5.1, 5.5.2 and 5.5.3, we present the TCO analysis results with cost figures derived from the European market. In section 5.5.4, we study the indoor system TCO providing cost retrieved from the Chinese market. By comparing results from different markets we intend to show how the TCO analysis conclusion varies between regions that have distinctive cost features. The results presented in this chapter are made under the assumption that the DAS carries traffic of a single mobile operator, whereas in many cases, multiple opera-

tors can share the same DAS infrastructure which makes the DAS economy more attractive to each individual operator. The latter case is studied and the results presented in G.

### 5.5.1 High Data-rate Offloading Scenario

In order to provide high speed data service to indoor areas with dense population (where there is a high possibility that many users are requiring high speed data service at the same time), a multi-sector DAS is needed. The number of sectors needed depends on the practical traffic need in-building. To make a fair comparison in the TCO analysis, the same traffic demand should be supported by the considered indoor systems. It is thus necessary to evaluate the radio performance by system simulations. Then, system TCO is compared in combination with and weighted by their corresponding system capacity.

As the LTE FAPs are by default a MIMO base station and to ensure that the same peak data rate is experienced by mobile users, we assume that a dual-antenna MIMO DAS is used and compared to Femto system. In the first phase, simulations<sup>7</sup> are run to evaluate the overall data throughput of each system. The performance result and the pre-BH TCO are both presented in Figure 5.7 and Figure 5.8 with another important KPI, normalized-cost-per-MB/user/day. The normalized-cost-per-MB/user/day is the system pre-BH TCO normalized by the maximum system capacity, which indicates the efficiency of cash investment in terms of incremental service quality. In the second phase we made a case study for the site-specific building with certain traffic load. We show the proper system configurations of DAS and Femto system respectively and demonstrate their cost. Furthermore, instead of using a constant traffic load, we make a prediction of the traffic demand growth on a yearly basis. According to the in-building traffic evolution, a system upgrade is required at different years during the investigated period; the accumulative pre-BH cost is compared between DAS and Femto systems.

1. Phase one: Cost efficiency, pre-BH TCO normalized by system capacity

The comparison of TCO along with the performance of different MIMO systems is given in Figure 5.7 and Figure 5.8. The Femto system is shown as having 12 access points as an example. In the figures, the bars in the front-most row show the pre-BH TCO (in unit of hundred Euros); the bars in the middle row represent the system capacity (in unit of Mbps/user/day); and the bars in the last row represent the cost normalized by capacity.

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<sup>7</sup>The same simulation configuration, except for the new building model, is applied as simulations conducted in Chapter 4. Unless otherwise stated, simulation assumptions are the same as used to obtain results in Chapter 4.

According to the result shown in Figure 5.7, the low-cost Femto (250 Euro/Femto) has an absolute advantage in this application due to both low pre-BH TCO and high demonstrated capacity, thus low normalized cost per Mbps. When the Femto price is high (800 Euro/Femto), the advantage of Femto lies in its high capacity which leads to relatively low normalized cost compared to any DAS configuration. The DAS using Macro base stations is relatively un-economical in both absolute value of pre-BH TCO and the normalized cost against capacity, because of the high cost of the base station equipment. The use of Pico base stations leads to less expensive DAS systems, which is shown in Figure 5.8. The pre-BH TCO of a 3-sector DAS can be lower than the Femto system with high-cost Femtos. However, benefiting from the high system capacity, the Femto system always has the lowest normalized cost per capacity unit. This makes the Femto system the more economical solution in high data rate and dense data service demand applications.

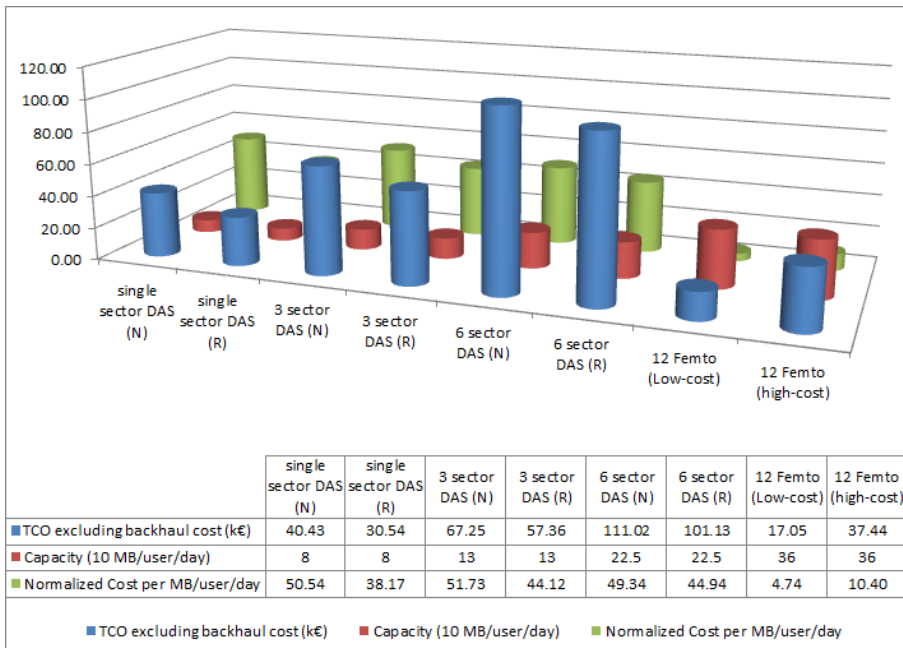


Figure 5.7: TCO comparison of LTE MIMO DAS (using Macro eNodeB) and Femto system.

We have been using the normalized-cost-per-MB/user/day as a critical indicator to evaluate the efficiency of cash investment. This is true when the customer traffic demand can exploit the excessive system capacity where the more capacity offered by the system the more revenue generated. In some other cases, when the data traffic need in the building is low, and the required data speed is moderate, the normalized-cost-per-MB/user/day is no

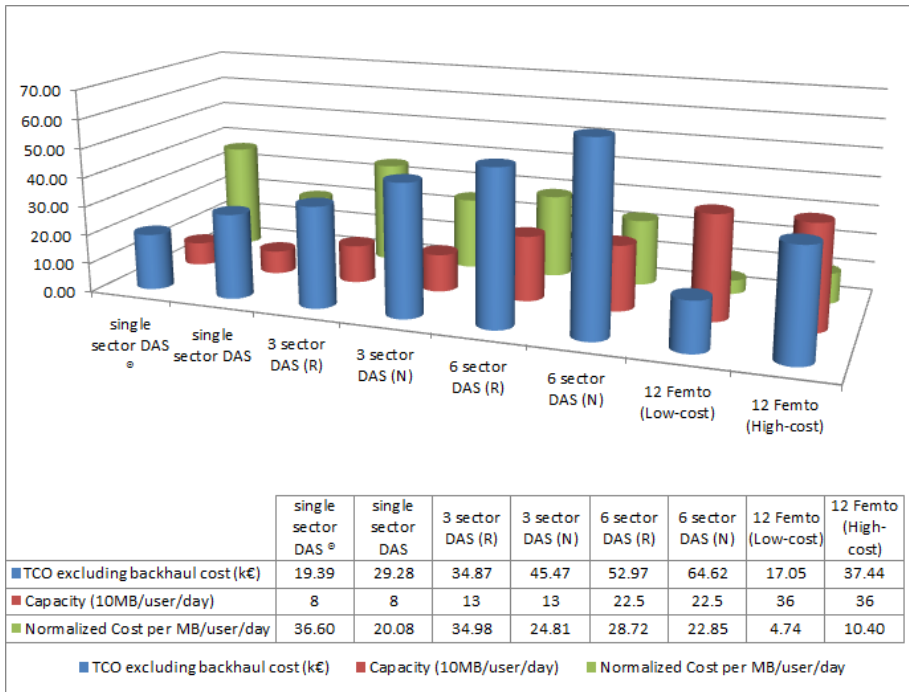


Figure 5.8: TCO comparison of LTE MIMO DAS (using Pico eNodeB) and Femto system.

longer a suitable KPI to examine the advantage of systems. It is because the excessive capacity, for example the high capacity offered by the Femto systems, can hardly bring any benefit in terms of revenue per user, as there is no user to consume and pay for the high capacity. In this case, the pre-BH TCO (demonstrated by the bars in the front-most row) is a better means of comparing different systems. We will analyze this particular scenario in section 5.5.2.

## 2. Phase two: Case study with traffic evolution

For any site-specific building with known traffic demand, the TCO of indoor DAS and Femto systems shall be compared provided they can both support the instantaneous traffic need. Essentially, we want to know how many sectors of DAS or how many Femtocells are needed to support a certain high traffic load. Through simulation it is found that to support the traffic load of an average daily user downlink data amount of 100 MB<sup>8</sup> in

<sup>8</sup>We assume that the indoor user density is 0.1 user/m<sup>2</sup>, traffic generated only during the working hours 8 hours/day. As the total indoor area is 15,000 m<sup>2</sup>, the average system throughput should be  $TP \geq (15000 \text{ m}^2 \cdot 0.1 \text{ user/m}^2 \cdot 100 \text{ MBps}) / (8 \text{ hours/day} \cdot 3600 \text{ seconds/hour}) =$



the office building shown in Figure 5.2, either a MIMO DAS composed of 3 LTE sectors (one sector on each floor) or 12 Femtocells are needed.

Furthermore, it is also important to see when the traffic load keeps growing how the system should evolve and how much incremental cash investment will occur. For this purpose, a model with an annual accumulated traffic increase by 25% is used for the duration of a 9 year period, presumably from 2012 to 2020. An initial in-building user traffic need of 100 MB/user/day is assumed the first year. In the last year, the average user traffic need reaches up to around 600 MB/user/day. The yearly evolution of traffic volume is shown in Table 5.3. The downlink system level simulation is conducted in

Table 5.3: Yearly Traffic Evolution.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
Traffic Volume per user per day in Mega-Byte	100	125	156	195	244	305	381	476	596

the building introduced in section 5.3 Figure 5.2. The building is assumed to be located in a macro coverage hole. In the simulation, an LTE system of 10MHz downlink bandwidth in the 2.6 GHz band is assumed. Other system settings can be found in Appendix B and Appendix F.

The results shown in Table 5.4 and Table 5.5 are phrased in terms of the needed upgrade at the beginning of the respective years to support the accumulated traffic growth. The selected DAS configuration is chosen from a predefined simulated set, which includes single-sector MIMO DAS, 3-sector MIMO DAS and 6-sector MIMO DAS. So in our simulation the DAS can have a maximum of 6 LTE sectors. In the beginning of year 2015, the 3-sector DAS has to be upgraded to be 6-sector DAS to feed the increased traffic demand. Such a DAS can provide the required capacity until the year 2018, and will be lacking enough capacity in the later years. Femto can still meet the traffic need at the end of year 2020, by deploying 18 Femto cells within the building.

Table 5.4: Timing of System Upgrade with DAS Solution.

Period (year)	2012-2014	2015-2017
System configuration that supports the traffic demand	3-sector MIMO	6-sector MIMO

The corresponding cost associated with the system initial deployment and future upgrade starting from the year of 2012 to the year of 2017 is shown in

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5.2MBps =41.7Mbps.

Table 5.5: Timing of System Upgrade with Femto Solution.

Period (year)	2012-2019	2020
System configuration that supports the traffic demand	12 MIMO Femto <sup>9</sup>	18 MIMO Femto

Figure 5.9. According to the upgrade path given by Table 5.4 and Table 5.5, for Femto systems, 12 Femtocells are deployed at the beginning of the year 2012. In mid-2014, replacement of all FAPs occurs due to the presumed depreciation of 2.5 years; and this is followed by another replacement in 2017. For DAS, a 3-sector DAS is deployed at the beginning year. In the year of 2015, the system has to be upgraded to have 6 sectors, and finally, the last costs are added in 2017 due to replacement of outdated equipment (5 years depreciation). Both systems can operate until the year 2019 before any more devices reach their period of depreciation. However, by the year of 2018, the DAS can no longer support the required capacity and will be operating at a much lower capacity compared to Femto.

We now take a look at the pre-BH TCO of DAS and Femto system in the demonstrated case. The overall TCO of the Femto system until the year of 2017 is around 22,000 € with low cost FAP and 50,000 € with high cost FAP. The cost of the DAS ranges from 62,000 € to 140,000 €. Both Femto systems with either high or low cost FAPs exhibit cost advantages over the DAS. In particular, the Femto system with low cost FAPs has an overall pre-BH TCO that is only one third of the Pico DAS and one fifth of the Macro DAS. The high cost of the DAS is caused by the small coverage area per sector and high CAPEX per sector. By using Macro eNodeB as signal source, the capital expenditure on base station equipment is slightly over 6,500 € per sector, or in this case, 6500 € per floor. Taking the initial deployment of a 3-sector DAS (Macro) as an example, the base station equipment alone accounts for a CAPEX of 1.3 €/m<sup>2</sup>, while the CAPEX of a 12-Femtocell system in the same building is only 0.4 €/m<sup>2</sup> for low-cost FAPs.

In this section we examined the indoor deployment solution providing high data-rate and high capacity in a site-specific building. From the above discussions we can see that the Femto system has an obvious advantage in scenarios where high data-rate and high traffic volume services are demanded. The Femto system exhibits lower cost and higher capacity than the DAS. The DAS is less cost efficient than Femto, because it is more expensive to add capacity of sectors in the DAS than adding Femtocells in the Femto system, due to the expensive base station devices used by DAS. Besides this site-specific case, what if the coverage size per sector or even the price of base station changes? We will try to address this question in the next subsection. In Section 5.5.2, we will make a more general analysis, examining the impact on the cost comparison when the coverage size of

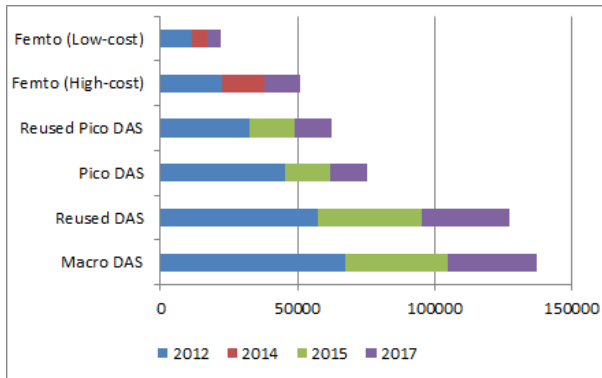


Figure 5.9: The NPV of invested cash flow for system construction and upgrading until the year 2017.

one sector or the price of base station varies.

### 5.5.2 Coverage Oriented Scenario

In some other cases of in-building deployment, high speed data traffic occurs only occasionally. The main goal is to provide ubiquitous voice coverage while the number of simultaneous data users is small. In this case, we assume that the traffic demand in the coverage area can be supported by a single LTE sector. We study the TCO as a function of the covered area. According to the building size, we sort the buildings into 3 categories:

- Small-size building: building size less than 15,000  $m^2$ ;
- Medium-size building: building size between 15,000 and 40,000  $m^2$ ;
- Large-size building: building size exceeds 40,000  $m^2$ .

From the previous results we notice that the cost of the DAS can be divided into two parts: the cost that relates to the distributed system and the cost that relates to the central system. The former is those parts whose total cost depends on the coverage area, including mainly the remote antennas, cables, couplers and splitters, etc, which has a unit price per square meter ( $e/m^2$ ). The remaining part of the system is invariant of the coverage size<sup>10</sup>. It includes mainly the base station equipment, backhaul equipment and site furnishing. The cost of the central

<sup>10</sup>Note that the following assumption is applied here: regardless of coverage size, only a single LTE sector is used to feed the DAS as signal resource.

system should be constant for the DAS under the single-sector assumption. The pre-BH TCO of the DAS can be expressed as in Equation (5.9).

$$TCO_{DAS} = TCO_{central} + TCO_{distributed} \times A_{DAS} \quad (5.9)$$

Where  $TCO_{DAS}$  and  $TCO_{central}$  represent the TCO of the DAS and the TCO of central system respectively,  $TCO_{distributed}$  is the unit price ( $e/m^2$ ) of the distributed system, and  $A_{DAS}$ <sup>11</sup> is the per-sector indoor coverage size of the DAS in square meter. If the DAS is a multi-sector DAS,  $A_{DAS}$  is the average coverage size per sector.

Similarly, the cost of Femto system can be modeled as a function of the coverage size by assuming a fixed coverage size per Femtocell. The pre-BH TCO of Femto system can be expressed by Equation (5.10).

$$TCO_{Femto\_system} = TCO_{FAP} \times \left\lceil \frac{A_{DAS}}{A_{FAP}} \right\rceil \quad (5.10)$$

where  $TCO_{Femto\_system}$  and  $TCO_{FAP}$  represent the pre-BH TCO of the Femto system and the pre-BH TCO of a single Femtocell,  $A_{FAP}$  is the average coverage size per Femtocell, and the sign  $\lceil \rceil$  means to round to the nearest larger integer.

We summarize the parameters used in Equation (5.9) and (5.10) in Table 5.6 based on the same cost assumptions as in previous sections. The pre-BH TCO estimation is shown in Figure 5.10 and Figure 5.11 with in-building size up to 25,000 square meters for newly constructed and reused existing DAS, respectively. Note that when the coverage area increases, the number of Femtocells increases. However, for DAS systems, it is only the distributed system, excluding the expensive base stations, that adds to the total cost increase.

In Figure 5.10(b), the same assumption is made for the DAS and Femto system that dual-antenna is used at base station side. The same peak user data rate is guaranteed for both indoor systems. Overall, the (low-cost) Femto system has a financial advantage over a newly constructed MIMO DAS. Building a new MIMO DAS is not seen cost efficient as compared to the Femto system. Passive DAS with Pico base stations is an alternative economical solution for small and medium-size buildings when per Femto cost is high. The cost of DAS can be reduced by deploying a single-antenna system instead of a dual-antenna system. The results can be seen in Figure 5.10(a). The cost of the Femto system will be higher than SISO DAS as the coverage area increases. The trend is clearly that for large-size buildings, the (low-cost) Femto system will eventually become more expensive, and the SISO DAS becomes a cheaper solution than the Femto system. The (low-cost) Femto system is more financially appealing for small and Medium-size buildings.

<sup>11</sup>Due to the large cable attenuation, we enforce the maximum coverage of the passive DAS fed by a single Pico base station to be no larger than the building model used in this chapter, which has 15,000  $m^2$  indoor area in total.

Table 5.6: Parameters for TCO Model with Variant Coverage Size.

MIMO DAS (5-year pre-BH TCO)		
	$TCO_{central}$	$TCO_{distributed}$
	MIMO/SISO	MIMO/SISO
Macro DAS (New)	19331/12372 €	1.407/0.844 €/m <sup>2</sup>
Macro DAS (Reuse)	19086/12066 €	0.661/0.155 €/m <sup>2</sup>
Pico DAS (New)	5944/5591 €	1.556/0.92 €/m <sup>2</sup>
Pico DAS (Reuse)	5699/5346 €	0.69/0.132 €/m <sup>2</sup>
Femto system (5-year pre-BH TCO)		
	$TCO_{FAP}$	$A_{FAP}$
Low-cost FAP	1421 €	1250 m <sup>2</sup>
High-cost FAP	3120 €	1250 m <sup>2</sup>

However, this conclusion is quite sensitive to the price of the Femtocells as we can read from the example given by the high-cost Femto. As the price of FAPs rises, the advantage of the Femto system shrinks or even diminishes.

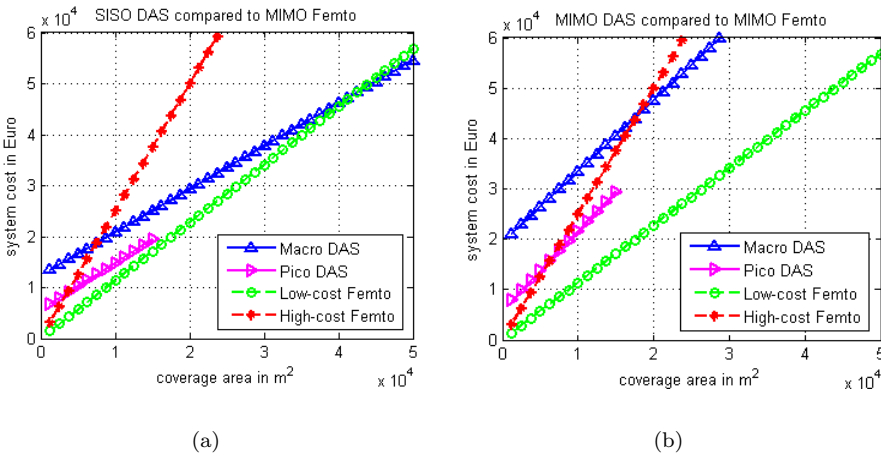


Figure 5.10: TCO of indoor systems (Femto and newly constructed DAS) as a function of per-sector coverage area.

Results are shown in Figure 5.11 for scenarios that a DAS is already present, and the distributed system can be reused in the building. In general, the cost of DAS increases much slower than the cost of Femto. In the MIMO case in Figure 5.11(b), we get similar conclusions as in the previous paragraph. Comparing to a dual-antenna MIMO DAS, the (low-cost) Femto system is still the less expensive choice unless the coverage size is larger than 40,000 m<sup>2</sup>. When considering a SISO DAS, we see that the increase of cost of the reused DAS is almost constant because

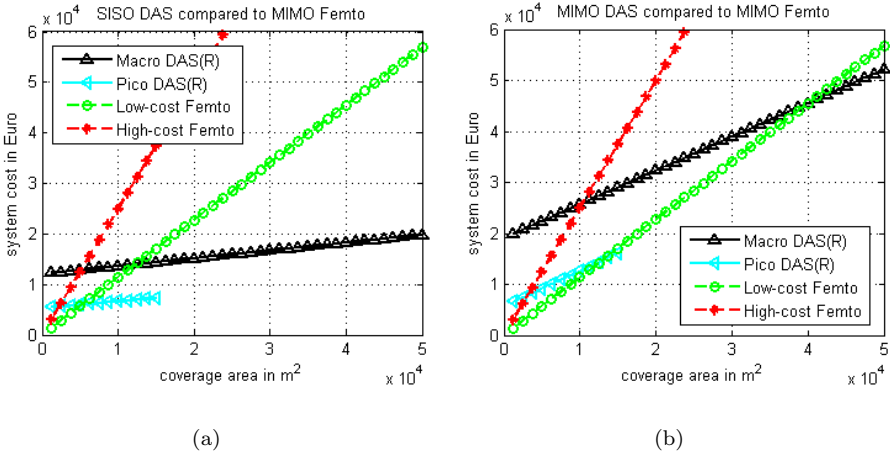


Figure 5.11: TCO of indoor systems (Femto and reused existing DAS) as a function of per-sector coverage area.

little cost is needed on the distributed system which means that there is little cost increase when the coverage area increases. In this case, the DAS is the most economical solution in most building types. The only exception is for extreme small-size buildings, which can be served by 2-4 Femtocells.

We can also interpret the results in this way: a large-size building requiring the capacity of multiple sectors can be viewed as a few single-sector coverage areas. When the per-sector coverage size is small, i.e. equal to the size of a small-size building, the Femto system is the most financially appealing solution although the total size of building is big. This conclusion is consistent with that made in the previous section. The reason is that when the coverage area of a single sector gets smaller and smaller, it approaches more and more the data-rate and a high capacity scenario, where we have shown that the Femto system is more cost efficient than the DAS.

In general, the result in this section shows that the (low-cost) Femto system is less expensive than the DAS unless the coverage size is very large or when an existing DAS can be reused, and single-antenna DAS is deployed. However, this advantage of the Femto system is sensitive to the cost of Femtocells as demonstrated by the high-cost Femto result. With high-cost Femtocells, the cost advantage resides only in very small coverage scenarios.

From equation (5.9) and (5.10), a clear relationship can be seen between  $TCO_{central}$ ,  $TCO_{distributed}$  and  $TCO_{Femtocell}$  in comparison of the system cost, see equation

(5.11).

$$\begin{aligned}
 & TCO_{DAS} - TCO_{Femto\_system} \\
 &= TCO_{central} + TCO_{distribute} \times A_{DAS} - TCO_{FAP} \times \left[ \frac{A_{DAS}}{A_{FAP}} \right] \\
 &\approx TCO_{central} + (TCO_{distribute} - \frac{TCO_{FAP}}{A_{FAP}} \times A_{DAS}) \quad (5.11)
 \end{aligned}$$

Firstly, when the unit cost ( $e/m^2$ ) of the distributed system is lower than that of the Femtocells, it is expected that as the coverage area increases, the DAS will ultimately be cheaper than the Femto system. We can otherwise say that the possibility that the DAS costs less than the Femto system relies on the condition that the unit cost of the distributed system is lower than that of the Femtocells, otherwise, the Femto system will always be a cheaper solution regardless of coverage size. We define the ratio of the two systems' coverage unit cost as  $R_c = TCO_{distribute} / \frac{TCO_{FAP}}{A_{FAP}} = \frac{TCO_{distribute} \times A_{FAP}}{TCO_{FAP}}$ .

Secondly, the speed at which the cost of the Femto system converges to the DAS, depends not only on the ratio of their unit cost  $R_c$  but also on the ratio of their base station (central system) cost. The latter is defined as  $R_{BS} = TCO_{central} / TCO_{FAP}$ . Let

$$TCO_{Femto\_system} = TCO_{DAS}$$

Then,

$$TCO_{FAP} \times \left[ \frac{A_{DAS}}{A_{FAP}} \right] = TCO_{central} + TCO_{distribute} \times A_{DAS}$$

Approximation can be made that,

$$TCO_{FAP} \times \frac{A_{DAS}}{A_{FAP}} = TCO_{central} + TCO_{distribute} \times A_{DAS}$$

Then we get,

$$\begin{aligned}
 TCO_{FAP} \times A_{DAS} &= TCO_{central} \times A_{FAP} + TCO_{distribute} \times A_{DAS} \times A_{FAP} \\
 A_{DAS} &= \frac{TCO_{central}}{TCO_{FAP}} \times A_{FAP} + \frac{TCO_{distribute} \times A_{FAP}}{TCO_{FAP}} \times A_{DAS} \\
 A_{DAS} &= R_{BS} \times A_{FAP} + R_c \times A_{DAS} \\
 A_{DAS} &= \frac{R_{BS}}{1 - R_c} \times A_{FAP} \\
 \frac{A_{DAS}}{A_{FAP}} &= N_{FAP} = \frac{R_{BS}}{1 - R_c}
 \end{aligned}$$

$N_{FAP}$  means the number of FAPs needed for the same coverage area of one single sector of the DAS. When more than  $N_{FAP}$  FAPs are required for covering the same

area covered by each one sector of the DAS, the Femto system will become more expensive than the DAS. In this sense,  $N_{FAP}$  is the threshold when the Femto system becomes more expensive than the DAS, the value of which is determined by  $R_{BS}$  and  $R_c$ . We plot  $N_{FAP}$  as  $R_{BS}$  ranges from 1 to 20, and  $R_c$  ranges from 0.05 to 0.8 in Figure 5.12.

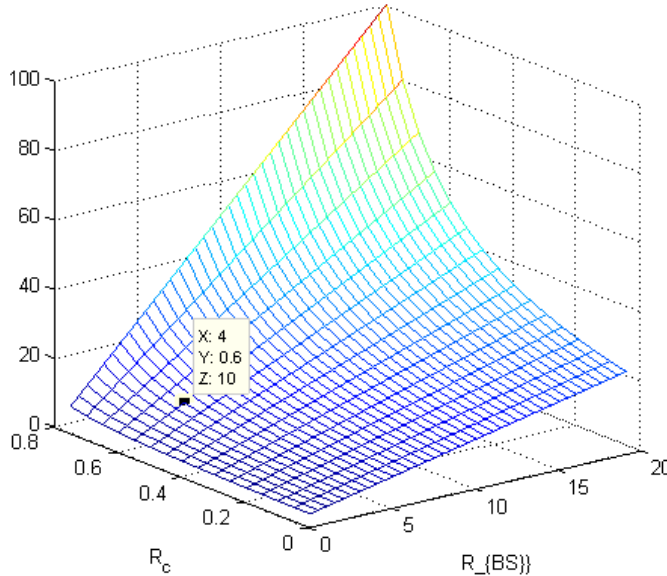


Figure 5.12: Number of FAPs in a single DAS sector coverage .

The highlighted point in Figure 5.12 shows the same case as comparing a reused MIMO Pico DAS and the (low-cost) Femto system ( $R_{BS} = 4.01$ ,  $R_c = 0.607$ ). It suggests that when the number of FAPs is equal to or greater than 10, the Femto system will be more expensive, which is consistent as shown in Figure 5.11(b). The number of FAPs employs a linear growth of  $R_{BS}$ . In the extreme cases,  $R_{BS}=1$  means a DAS fed by FAPs. It can be seen that when  $R_c$  equals 0.8, the Femto system that has less than 5 Femtocells is actually cheaper than a Femto DAS. The growth rate of  $N_{FAP}$  is exponential to  $R_c$ . It means that the Femto system has more cost advantage in a larger indoor area when  $TCO_{FAP}$  is low, or the coverage per Femtocell  $A_{FAP}$  is large, or the distributed system of DAS  $TCO_{distribute}$  is costly. Larger Femtocell coverage means that the Femto system becomes more economical in open indoor spaces where the signal attenuation is slower than in a dense office scenario. The costly DAS construction means either high device cost or high labor cost for installing the distributed system. Conversely, in buildings that have dense internal walls or blocks, and in markets where the labor cost is



low, the DAS will benefit. Similar examples will be shown in Section 5.5.4.

### 5.5.3 TCO with Variant BH Options

The backhaul connection can be provided to the in-building mobile systems by leased line, by micro-wave or by self-deployed fiber as described in detail in section 5.4.3. In some developed metropolitan areas, modern business buildings are already equipped with high-speed connection to the provider's network, or are easily connected without significant extra cost. However, in most cases, high data-rate backhaul is not directly accessible; and either leasing or installing self-owned backhaul is quite expensive. The cost of high data-rate backhaul is especially high. Some typical backhaul deployment cost is listed below in Table 5.7.

Table 5.7: TCO of variant backhaul solutions.

Backhaul TCO				
		Rate per month	Depreciation	5-year TCO
Leased line (combined TDM and Ethernet or Fiber)	Case 1 Low-cost	400 €	-	25,621 €
	Case 2 High-cost	1000 €	-	58,352 €
		CAPEX	Depreciation	5-year TCO
Microwave	Case 1 Low-cost	11,900 €	8 years	21,216 €
	Case 2 High-cost	11,900 €	8 years	32,337 €
		CAPEX	5-year TCO	
Self-owned Fiber	Case 1 500 m (short-distance)	53,800 €	20 years	18,573 €
	Case 2 1500 m (long-distance)	153,800 €	20 years	48,119 €

Mobile operators tend to use leased lines or build micro-wave backhaul at the roll-out phase to avoid the huge amount of upfront CAPEX investment at the early years. However, due to a longer depreciation period, fiber optic backhaul has shown long-term competitiveness in terms of lower TCO in Table 5.7. An example of TCO with backhaul cost is illustrated in Figure 5.13.

In the figure the comparison is made between a Femto system using 12 FAPs and a newly built MIMO Pico DAS system. The low-cost and high-cost of backhaul corresponds to 500 meter self-deployed fiber and high-cost leased line backhaul. The TCO cost of the DAS before applying backhaul is more than 70% higher than that of the Femto system, or even 2 times the cost of the Femto system. After the backhaul cost is added on top, the overall TCO of the single and three sector DAS is only 16% and 38% higher than the Femto system, respectively. The

result suggests that when the backhaul cost becomes significant and dominates the overall TCO (taking up more than 50% of TCO in our case) the advantage of Femto systems becomes marginal.

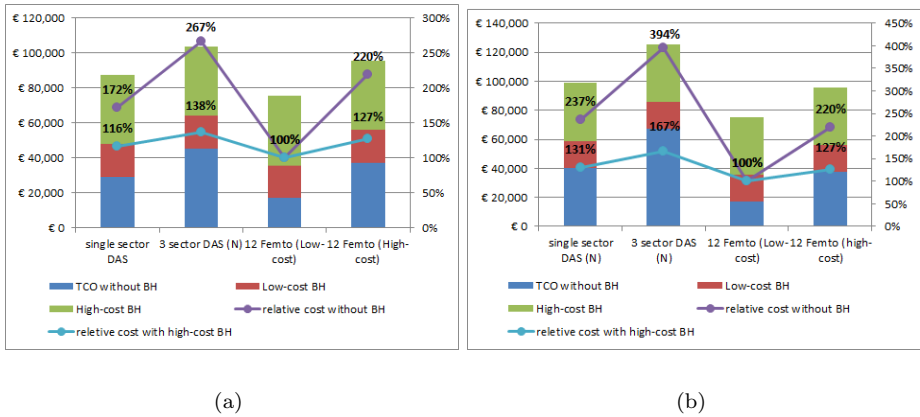


Figure 5.13: 5-year TCO with backhaul cost.

### 5.5.4 TCO Analysis with Distinctive Cost Feature of China Market

The TCO analysis made in the previous sections is based on cost figures derived from the European market. In such a market, the high labor cost is a major concern that contributes to the high cost of system deployment and maintenance, which is also a common phenomenon among the developed countries. The TCO results presented above thus represent and reflect well the business practice in the developed regions. In different regions or markets in the world, where the cost features are distinctive to those we adopted previously, the TCO result of each system changes accordingly. There are two major factors that differentiate the TCO characteristics between the markets of the developed regions and the developing regions. First, the labor cost in the latter case is quite low compared with that in the former case. The low labor cost leads to a significantly lower implementation cost of the DAS, brings down the operational cost of each system and also leads to much cheaper installation of fiber backhaul links than in the European cities. Secondly, due to the low cost of site visit, the system allows installing cheaper passive components that follow more relaxed quality standards.

A case study of the city of Beijing (China) is made in this section as an example representing the markets from the developing countries to show how these factors will alter the TCO comparison results. Detailed cost assumptions and price list

can be found in Appendix F. In general, except for the base station equipment, the CAPEX and IMPEX of the indoor system components in Beijing are one half of those in the developed countries. Such cost data is obtained directly from one of the incumbent Chinese mobile operator.

First, we make an overview of the changes made on the cost for the two indoor systems using the reduced cost value. In Figure 5.14(a) Figure 5.15(a), the figure presents the new TCO results. In Figure 5.14(b) Figure 5.15(b) are the corresponding TCO results using European market cost assumptions.

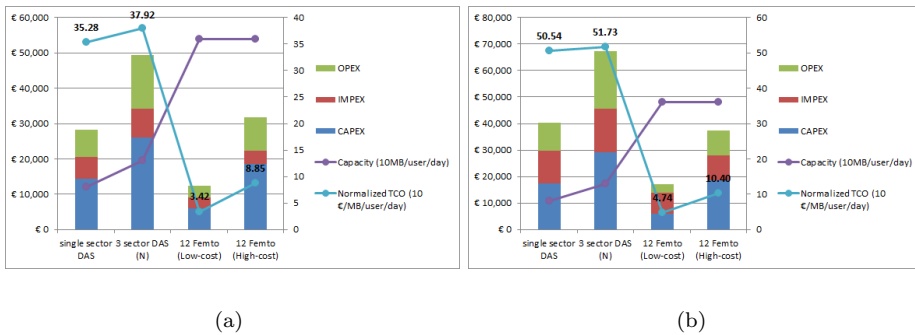


Figure 5.14: TCO and capacity comparison of indoor systems (Femto and newly constructed DAS using macro base station): (a) China Beijing case (b) European case.

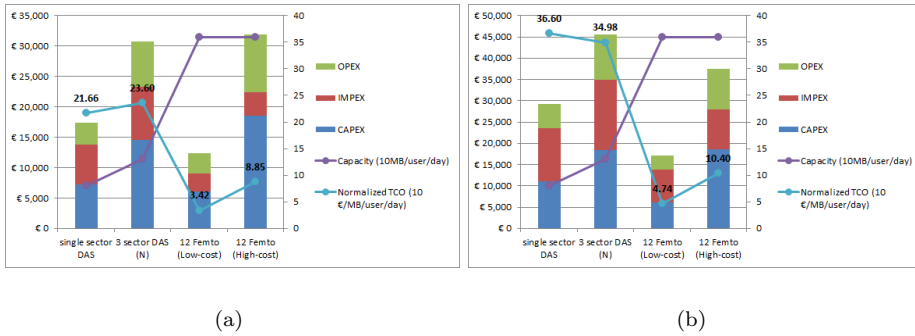


Figure 5.15: TCO and capacity comparison of indoor systems (Femto and newly constructed DAS using pico base station): (a) China Beijing case (b) European case.

Seen from the results, both systems experience cost reduction on the absolute TCO values, shown by the bar plot. The cost reduction is most obviously seen

on the IMPEX. Due to the fact that the IMPEX contributes largely to the DAS TCO, the cost reduction on the DAS is higher compared to the Femto system. However, even though the high cost Femto becomes more expensive than a three sector Pico DAS, the DAS is still a less economical solution for providing high data rate service, because the cost per MB of data of the DAS is still much higher than for the Femto systems. The same conclusion can be drawn by reading Figure 5.16. In the figure, the same assumption of yearly traffic evolution is applied as used in subsections 5.5.1. The cost efficiency of the Femto system for high data rate applications is also proved in developing countries.

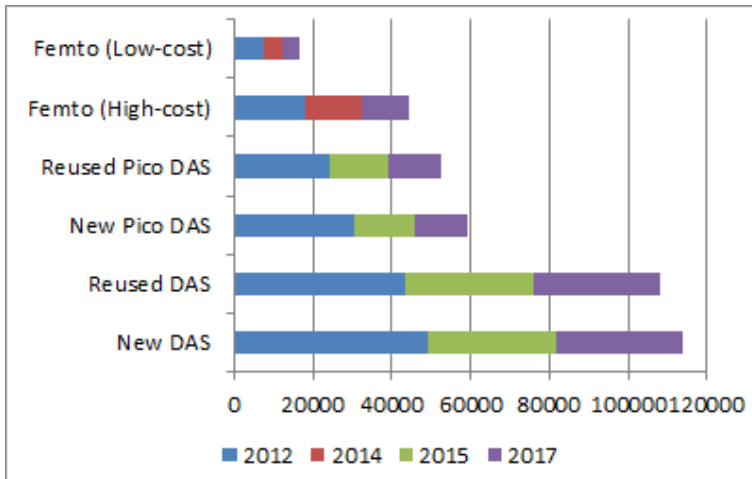


Figure 5.16: NPV of invested cash flow for system construction and upgrading until the year 2017 with assumed traffic evolution.

For the coverage-oriented deployment scenarios, the results can be referred to in Figure 5.17. Only the newly constructed DAS is considered here. Compared to the European case, the conclusion for building a MIMO DAS is the same that low-cost Femto system is the most economical solution while the advantage shrinks due to the raise of per FAP cost. When the Femto system is compared to a SISO DAS, with reduced labor cost, the DAS gains its advantages in medium-size buildings when the building is larger than 25,000  $m^2$ .

The most obvious changes are made on the backhaul related cost. Due to the extremely low cost of fiber deployment, a more feasible backhaul solution in China and similar countries is to install dedicated fiber link to the building.

Figure 5.18 demonstrates how the advantage of low-cost Femto system changes after the backhaul related cost is applied on each system. The low-cost and high-cost backhaul corresponds to the 500 meter and 1000 meter self-deployed fiber link. Contrary to the big difference shown in the European case comparing the

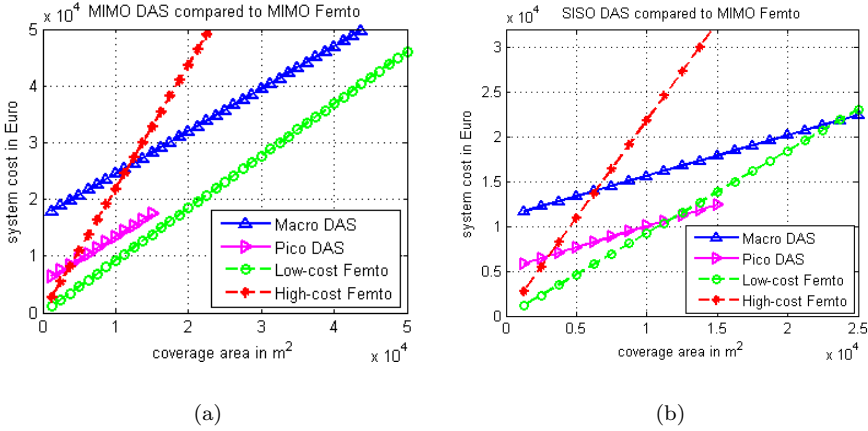


Figure 5.17: TCO of indoor systems (Femto and newly constructed DAS) as a function of the per sector coverage size.

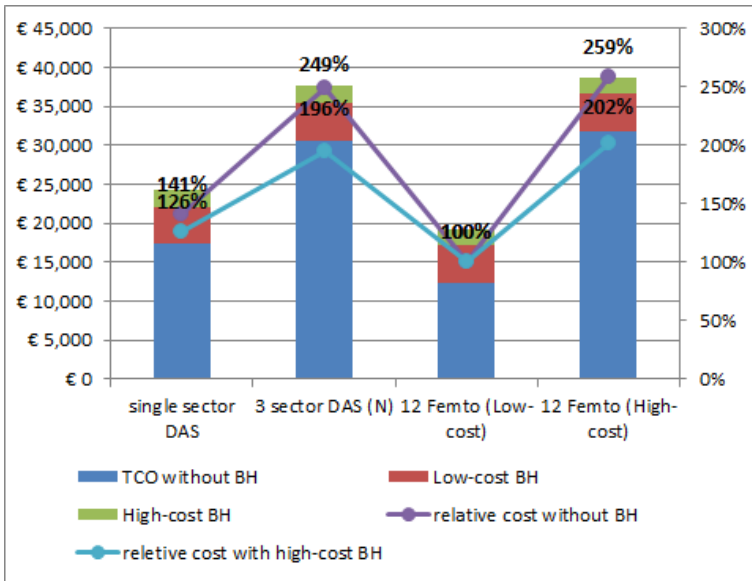


Figure 5.18: 5 year TCO with backhaul cost.

pre- and after- backhaul cost (Figure 5.13), the merit of low-cost Femto system remains high in the Beijing case. Even with backhaul cost added on top, a three sector DAS is still 96% more expensive than low-cost Femto system. Meanwhile, in the European case, this gain is reduced from 167% to only 38% without and

with backhaul.

## 5.6 Summary

In this chapter we conduct a financial economical analysis for indoor DAS and Femto system based on TCO analysis. We compare the TCO of the Femto system and passive DAS for the enterprise in-building networks. Within the scope of our analysis and the assumptions applied, we made our findings as follows:

- For very high data-rate in-building deployment, the Femto system has absolute advantage due to its much lower cost compared to the DAS.
- For coverage-oriented deployment with very limited user data traffic demand, DAS is the most economical solution in large-size buildings, and Femto is more economical for deployment in small-size buildings.

This conclusion is in general valid for the European market. The second bullet of conclusion is, however, sensitive to the price of the FAP. The sensitivity to the FAP price is considered in this study by assuming two categories of FAPs: a low-cost and a high-cost FAP. For a low-cost Femto system, it is almost always cheaper than deploying a MIMO DAS. For a high-cost Femto system, it seems to be only beneficial for very small sized buildings, where 3-4 Femtocells are enough to provide in-building coverage.

A clear cost advantage can be obtained when the suitable system is chosen in the above described scenarios on condition that backhaul connection is accessible at a minor cost. However, when the backhaul cost becomes significant compared to other costs, the TCO of the two systems may end up in the same range. The cost becomes a less critical issue when evaluating the two systems and gives way to other considerations.

However, different mobile operators are exposed to variant challenges in their own business model. Besides backhaul, the operators' experienced costs may deviate from the average level used in this study in many other aspects. These include more (or less) expensive site visits, operation-and-maintenance, or additional cost on Femto system management, etc. For this sake, sensitivity numbers of per Femto expense were used. The use of high value of Femto cost intends to help cover the possible expected price on device, QoS management and site visit for maintenance. As time moves forward, the backhaul cost will decline. When fiber is available, Femto becomes a more appealing approach for extending the indoor coverage and providing high data-rate. The results are shown with representative backhaul cost

values, but the developed cost model can also be supplied with the operators' own cost numbers to give an accurate estimation.

In the developing regions or markets where the cost feature is distinctive to the European market, the overall TCO comparison changes. We study the case of the city of Beijing in China as an example. The low labor cost in China brings down the cost of both the Femto system and DAS systems, however, with greater merits to the DAS. This makes the DAS more appealing in buildings of a widened size range. Unlike in the European case, the backhaul solution with self-owned fiber can be very cheap which may facilitate the wide deployment of the Femto systems in high data-rate applications.

# Conclusions

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The Distributed Antenna System (DAS) and Femtocells constitute two major In-building Wireless (IBW) options for efficient in-building coverage extension and capacity provision. This study makes an extensive examination based on these two systems for indoor network evolution towards the Long Term Evolution (LTE). In order to achieve a technology economical evaluation of high capacity indoor wireless solutions, the study is divided into two major aspects: radio performance evaluation and financial economical comparison. Firstly, their radio performance for indoor high-data-rate deployment is evaluated in the LTE downlink context. Possible system enhancement is proposed to improve system performance. Then the system cost analysis is conducted and compared between systems in distinctive applications.

In the first part of the thesis, the performance of these systems is investigated and compared in an office environment. To achieve ubiquitous indoor coverage and provide high capacity, the DAS and Femto systems need to be optimized with respect to the optimum number and locations of the (distributed) Access Point (AP)s. Such an optimization is highly coupled with the building structure and the indoor traffic demand. For the enterprise solution, the placement of the APs is assumed to be coordinated and optimal; however, performance of systems with non-optimal placement of APs is also investigated to study the sensitivity of the performance.

The DAS is less efficient in providing high speed, high volume mobile data services



than the multi-cell systems. However, the drawback of the enterprise Femto system is its vulnerability to inter-cell interference. In the worst case when the network is fully loaded (all cells are simultaneously transmitting over the whole bandwidth, e.g. during busy hours), the performance of the multi-Femto system is largely deteriorated due to heavy inter-cell interference. In this situation, many users do not achieve a satisfactory Quality of Service (QoS) because they are experiencing a poor Signal to Interference plus Noise Ratio (SINR) condition. To provide satisfactory cell-edge user experience, a Quality-Guaranteed (QG) scheduler is developed for such dense deployed multi-cell systems, which enforces the base station to allocate more radio resources to cell-edge users. With the help of such a scheduler, the multi-Femto system achieves more than doubled increase in cell edge user performance and number of supported QoS users. The improvement was made by the QG scheduler with little sacrifice on the overall system throughput compared to the commonly used equal-share scheduler.

Besides using the QG scheduler, the performance of the multi-cell system can be further increased by hard frequency reuse or by the proposed centralized coordinated scheduling system, Intelligent Distributed System (IDS). IDS first identifies the strongest interferers of a user, and by joint-scheduling, makes sure that the frequency resources allocated to the user will not be reused by its strong interfering cells. In case of the hard frequency reuse, the results, however, indicate that performance is sensitive to the placement of the Femto Access Point (FAP)s. The non-optimized FAP placement reduces the performance by 15% on supported user number and 60% on system throughput. Therefore, a good radio planning is required to ensure that the system is operating at its highest capacity. On the other hand, the proposed IDS automatically identifies the interfering cells and coordinates the transmissions accordingly. Therefore, it is stable and robust towards non-optimal AP placement. Also, it improves the SINR while maintaining high bandwidth utilization efficiency. The gain of using IDS over the plain Femto system with optimized AP location is about 10%.

Outside the busy hours, the network is normally partially loaded (only parts of the cells are connected to active users and transmitting simultaneously). In this situation, the multi-Femto system demonstrates much higher capacity compared to the DAS. The proposed centralized coordinated scheduling system can further improve the performance in comparison to the DAS and Femto systems.

In the second part of the thesis, we investigate the financial economic analysis for indoor DAS and Femto systems based on the total cost of ownership (TCO) analysis. The TCO is a financial estimate to determine the direct and indirect costs of a product or a system over a certain time period. We compare the TCO of the Femto system and the DAS for enterprise in-building deployments. Within the scope of our analysis and the applied assumptions we find that: 1) for very high data-rate in-building deployment, the Femto system has an absolute advantage due to its much lower cost (22,000 to 50,000 € for the evolution of the considered

network) compared to the DAS (62,000 to 140,000 €); 2) for coverage-oriented deployment with very limited user data traffic demand, DAS is the most economical solution in large-size buildings, whereas Femto is more economical for deployment in small-size buildings. The break-even point depends on the unit price of the FAP. However, when the backhaul cost becomes the dominant part of the TCO, it is less critical which of the two systems to choose from the cost point of view. It can be concluded that the vast adoption of enterprise Femtocells will start in indoor hotspots with high data traffic demand and high capacity backhaul accessible at minor cost.

Future work can be made to this work firstly on the design of the presented algorithms. Automatic switching from equal-share scheduling to quality-guarantee scheduling or switching from the HFR 1 to other partial reuse schemes can be developed depending on the instantaneous traffic load. Furthermore, the work can be applied in vast area network evolution studies with realistic indoor hotspot information, traffic growth statistics and accurate cost data tailored for each specific MNO.



# Joint Multi-cell Frequency Domain Scheduling for Downlink

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For the MAC-layer downlink packet scheduling of intelligent distributed system (IDS), we assume that the packet scheduling has to be assisted by the central controller, instead of committing separate scheduling by individual cells. In Chapter 2, we have briefly introduced the basic operation of the centralized coordinated scheduling procedure. The procedure is divided into two major operations. The first one is the identification of the strong interferer set for each user; the second one is the joint scheduling operation. The different ways of identifying the strong interferer set depend on the adopted radio resource sharing principle by the scheduler, which is described in detail in Chapter 3. This is done at each individual cell for all its serving users. Afterwards, the packet scheduling decision will be made jointly at the central controller for all the in-building cells (belonging to the same IDS).

Every scheduling instance (assumed per TTI), each cell passes the relevant information for packet scheduling to the central controller, and the scheduling decision will in turn be sent back to each cell for generating the downlink signal. The relevant information for the centralized joint scheduling, includes the ordinary information used for single-cell packet scheduling, i.e. the available spectrum resource on each cell, the downlink channel measurement reported by the user equipment, retransmission decision, etc. However, it also contains the strong interferer set

for all users and/or the user's QoS target. With all the required information, we introduce the joint scheduling procedure in the follow section.

## A.1 Multi-cell Joint Scheduling

Define  $\Omega_k$  as the set of blocked cells for user  $k$ ;

$L_k$  as the number of elements of  $\Omega_k$ ;

$U_j$  as the set of users connected to cell  $j$ .

**step 0** Estimate the spectral efficiency for UE  $k$  on the  $i^{th}$  PRB ( $\mu_{i,k}$ ); then calculate the number of PRBs to allocate for UE  $k$ , denoted by  $\lambda_k$ <sup>1</sup>. Do the same for all active UEs.

**step 1** Generate the scheduling matrix, as  $\mathbf{W} = [W_1^T, \dots, W_i^T, \dots, W_M^T]^T$ , and  $W_i = [w_{i,1}, \dots, w_{i,j}, \dots, w_{i,N}]$ , where  $1 \leq j \leq N$  is the cell index, and  $1 \leq i \leq M$  is the PRB index.

The matrix is generated by selecting the UE that maximizes  $w_{i,j}$  for each cell  $j$  on PRB  $i$ , according to:

$$k_{i,j} = \underset{k \in U_j}{\operatorname{argmax}} \left\{ \frac{\mu_{i,k}}{L_k + 1} \right\} \quad (\text{A.1})$$

$$w_{i,j} = \mu_{i,k_{i,j}} \quad (\text{A.2})$$

Some explanations for step 1:

The reason for dividing the spectrum efficiency  $\mu_{i,k}$  by  $L_k + 1$  is that, the UEs who need to block the transmission on the other cells would take up  $L_k + 1$  times that calculated in  $\lambda_k$ . Thus,  $\frac{\mu_{i,k}}{L_k + 1}$  is the actual spectrum efficiency for UE  $k$ , taking the PRBs blocked on other cells into consideration.

**step 2** Choose a PRB to schedule. Select the PRB which has the highest weighting value  $w$  among the total ( $N \times M$ ) PRBs of  $N$  cells:

$$[m, n] = \underset{i,j}{\operatorname{argmax}} \{w_{i,j} | i = 1, \dots, M, j = 1, \dots, N\}$$

The chosen PRB is the  $m^{th}$  PRB on the  $n^{th}$  cell. Then find the user index  $k_{m,n}$  which gives the weighting factor  $w_{m,n}$ , and its correspondence strong interferer set  $\Omega_{k_{m,n}}$ .

**step 3** Allocate the  $m^{th}$  PRB of cell  $n$  to user  $k_{m,n}$

Set  $w_{m,n} = 0$

Set  $w_{m,x} = 0$ , where  $x \in \Omega_{k_{m,n}}$

to indicate the assigned or blocked PRBs.

---

<sup>1</sup>The calculation of  $\lambda$  is given in section A.2.

if  $\Omega_{k_{m,n}}$  is not empty  
 recalculate the weighting factor  $w_{m,j'}$  on the  $m^{th}$  PRB of all the unassigned and unblocked cells ( $j' = 1, \dots, N; j \neq n, x$ ), using Equation( A.1) and ( A.2) with updated  $L$  value:

$$L_k = \text{length}(\Omega_k \cap \overline{\Omega_k \cap \Omega_{k_{m,n}}})$$

Update matrix  $\mathbf{W}$ .

end

Some explanations for step 3:

The operation of  $\Omega_k \cap \overline{\Omega_k \cap \Omega_{k_{m,n}}}$  is to remove the effect of already blocked cells on calculating  $L_k$ . This gives priority to UEs that have the same strong interferer cells as UE  $k_{m,n}$ , for a smaller value of  $L$  leads to a larger value of  $w$ .

**step 4** Denote the number of PRBs already assigned for user  $k_{m,n}$  as  $\lambda'_{k_{m,n}}$ .

if  $\lambda'_{k_{m,n}} < \lambda_{k_{m,n}}$ ,  
 go to (step 2) and continue.

else if  $\lambda'_{k_{m,n}} = \lambda_{k_{m,n}}$   
 Set  $\mu_{i,k_{m,n}} = 0$   
 Update  $\mathbf{W}$  using Equation( A.1) and ( A.2).

if  $\mathbf{W} \neq 0$   
 go to (step 2) and continue.

else if  $\mathbf{W} = 0$ ,  
 allocate the remaining unassigned and unblocked PRBs equally among UEs

end

end

Some explanations for step 4:

When the number of assigned PRBs at this TTI for a single UE  $k$  ( $\lambda'_k$ ) reaches the designated value ( $\lambda_k$ ), the scheduler should temporarily eliminate this UE from being scheduled before all other UEs have been allocated their designated number of PRBs. When matrix  $\mathbf{W}$  becomes an all zero matrix, it means that all the UEs have been allocated their designated number of PRBs. At this point, if there are still PRBs left unassigned (and unblocked), these PRBs will be distributed fairly among UEs.

## A.2 Calculation of $\lambda$

The number of PRBs to be allocated to each user at every scheduling instance,  $\lambda$ , depends on the type of scheduler used. In our study, we assumed two types of schedulers: one follows the resource equal share principle and the other tries to guarantee each user's throughput requirement. According to these two principles, we describe the way we used to calculate  $\lambda$  in the following paragraphs. When investigating the frequency-domain packet scheduler (FDPS), we assume we have a transparent time-domain packet scheduler (TDPS), which allows all users to be passed to the FDPS at each TTI.

### A.2.1 Calculation of $\lambda$ assuming equal-share principle

Define  $M$  as the total number of available PRBs of each cell;

$U'_j$  as the set of users served by cell  $j$  plus the users who identify cell  $j$  as in their strong interferer set;

$K'_j$  as the number of elements in  $U'_j$ ;

$\Omega_k$  as the strong interferer set of user  $k$ ;

$\delta_j$  as the number of PRBs each user (who belong to set  $U'_j$ ) can be allocated on cell  $j$  according to equal-share principle;

$\lambda_k$  as the number of PRBs user  $k$  can be allocated on its serving cell.

First we rank  $K_j$  according to its value from high to low, so that  $K_{j_1} \geq K_{j_2} \geq \dots \geq K_{j_N}$ . We get the sequenced cell index  $I = \{j_1, j_2, \dots, j_N\}$ . Following the equal-share principle, we could expect that the number of PRBs to be shared by each user on different cells follows  $\delta_{j_1} \leq \delta_{j_2} \leq \dots \leq \delta_{j_N}$ . To calculate the number of PRBs to be allocated to the users of each cell, we initialize  $\delta_j = M$ , ( $j \in \{1, 2, \dots, N\}$ ) and start with the first listed cell in the index sequence  $I$ .

$$\delta_{j_1} = \left\lfloor \frac{M}{K_{j_1}} \right\rfloor \quad (\text{A.3})$$

For the users associated to cell  $j_1$  ( $k \in U'_{j_1}$ ), we can get that,

$$\lambda_k = \min \{\delta_i | i \in \Omega_k\} \quad (\text{A.4})$$

For the second listed cell, we define  $\Phi$  to be the set of users which are common elements in both sets  $U'_{j_1}$  and  $U'_{j_2}$ , so that  $\Phi_2 = U'_{j_1} \cap U'_{j_2}$ .  $Length(\cdot)$  is the number

of elements of a set.

$$\delta_{j_2} = \left\lfloor \frac{M - \sum_{k, k \in \Phi_2} \lambda_k}{K_{j_2} - \text{Length}(\Phi_2)} \right\rfloor \quad (\text{A.5})$$

For the users associated to cell  $j_1$  and  $j_2$  ( $k \in U'_{j_1} \cup U'_{j_2}$ ),

$$\lambda_k = \min \{\delta_i | i \in \Omega_k\} \quad (\text{A.6})$$

For the  $x^{\text{th}}$  ( $x > 2$ ) listed cell,  $\Phi_x = (U'_{j_1} \cup U'_{j_2} \cup \dots \cup U'_{j_{x-1}}) \cap U'_{j_x}$ .

$$\delta_{j_x} = \left\lfloor \frac{M - \sum_{k, k \in \Phi_x} \lambda_k}{K_{j_x} - \text{Length}(\Phi_x)} \right\rfloor \quad (\text{A.7})$$

For the users associated with cell  $j_1$  to  $j_{x-1}$  ( $k \in U'_{j_1} \cup U'_{j_2} \cup \dots \cup U'_{j_{x-1}}$ ),

$$\lambda_k = \min \{\delta_i | i \in \Omega_k\} \quad (\text{A.8})$$

### A.2.2 Calculation of $\lambda$ assuming quality-guarantee principle

Define  $X_k$  as the target QoS throughput of user  $k$  in *bps*;

$T$  as the length of time interval of a scheduling instance (normally 0.001s);

$B$  as the effective bandwidth per PRB;

$\mu_k$  as the average achievable spectrum efficiency throughout the whole available bandwidth.

The number of PRBs to be assigned to each user depends in this case upon the required minimum throughput ( $X$ ) of the user and its achievable spectrum efficiency ( $\mu$ ). It can be expressed by,<sup>2</sup>

$$\lambda_k = \left\lfloor \frac{X_k \times T}{\mu_k \times B} \right\rfloor. \quad (\text{A.9})$$

---

<sup>2</sup>If the TDPS allows only a number of  $N_{TD}$  users to enter the FDPS,  $N_{TD} < N_j$ ; and the odds of each user being scheduled by TDPS is equal in average over time. Then,

$$\lambda = \left\lfloor \frac{X_k \times T}{\mu_k \times B} \cdot \frac{N_j}{N_{TD}} \right\rfloor$$





# Simulation Assumptions

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This appendix describes the simulation assumptions for each considered scenario used in this thesis, including the site-specific office scenarios and the generalized building scenario. The former is based on a real building, and the large scale path loss is derived from real-life measurement; the latter is based on the proposal in [103]. The LTE system related parameters are taken according to [187].

## B.1 Building Model and Large Scale Path Loss Model

### B.1.1 Site-specific office building Scenario

The site-specific building is a 3-floor office building with overall dimensions of 15 meters wide and 50 meters long. The office building is one among many in the NOVI park located in Niels Jernes vej, in the city of Aalborg, Denmark. The detailed floor plan is illustrated in Fig. B.1, where each floor has a long corridor with office rooms of variant sizes at its side. The building is assumed to be located in a macro environment, as shown in Fig. B.2, where the building is facing the main beam direction of one sector of the nearest macro site. The nearest macro site is at a distance of 333 meters away and the propagation of signal from the outdoor antenna to the building is Non-Line of Sight (NLOS). The simulated

average interference signal level is around  $-89$  dBm inside the building, with the side facing the main beam at an approximately 9dB higher interference level than the opposite side.

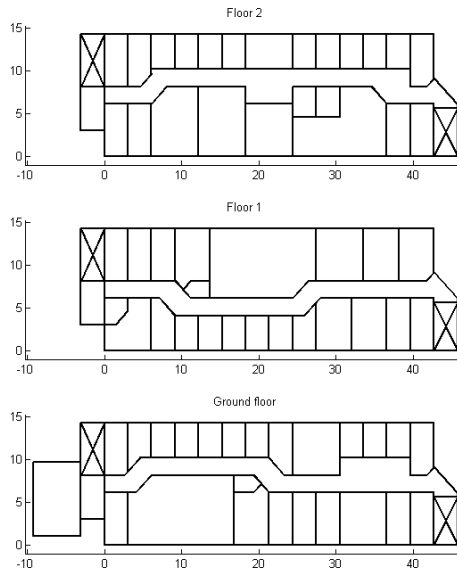


Figure B.1: Site-specific office building model with sampled measurement spots.

Fig. B.2 also illustrates the possible user locations. The user locations are selected randomly from 322 sampled measurement spots. The sampled measurement spots cover the whole building area and give an almost uniform distribution inside the building. The walls inside the building are all thin walls with small attenuation loss; only the outer walls are assumed thick with high attenuation loss. The windows of the outer wall are shielded, which gives even higher attenuation loss than the outer wall. The high attenuation loss offers ‘isolation’ of the building against the radiation from outdoor antennas and helps to improve the in-building SINR condition.

All large scale path loss values for the site-specific building have been collected from a measurement calibrated path loss prediction tool of the building. The tool is introduced in detail in [104]. The predicted value has a residual error scatter with standard deviation of as low as 4.4 dB. The predicted path loss values account for most of the correlated shadowing effect caused by building structure and furnishings. The unaccounted random part follows closely a log-normal distributed variable and has been accounted for in the simulations by adding an i.i.d. lognormal variable with 3 dB standard deviation to every predicted path loss value. The

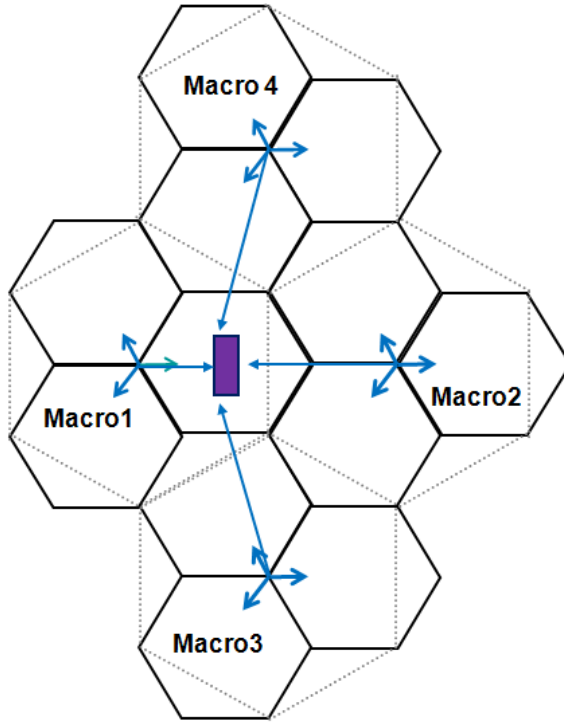


Figure B.2: The building location in the macro network environment.

path loss prediction model (in the decibel scale) can be expressed as:

$$PL = AF + 10\log_{10}(d^2) + \sum_i c_i L_i + G_a \quad (\text{B.1})$$

$AF$  is the antenna coupling factor. The  $AF$  is defined in Eq. B.2 as a function of the wavelength  $\lambda$ . It corresponds to a value of 38.6 dB at the frequency of 2GHz over a one meter free space path.

$$AF = 10\log_{10}\left(\frac{\lambda}{4\pi}\right)^2 \quad (\text{B.2})$$

In Eq. B.1,  $d$  is the path distance in meter,  $G_a$  is the antenna gain. A logarithmic attenuation  $L_i$  is associated with the structure or material of the physical partitions through the path the signal traverses. It can be interpreted as material penetration loss, whereas it is in fact an effective attenuation with accounts for

other propagation phenomena along the direct path passing through the structure. The variable  $c_i$  counts for the number of partitions of type  $i$  with attenuation  $L_i$ . For outdoor-to-indoor path loss predictions, an additional distance-dependent factor of  $\alpha 10 \log_{10}(d)$  is considered to represent the typical outdoor Non-Line of Sight (NLOS) propagation property. When assigning the exponential factor  $\alpha = 1.76$ . It makes the overall distance-dependent exponential factor to be 3.76, which is consistent with most outdoor path loss prediction models under Non-Line of Sight (NLOS) conditions.

### B.1.2 Generalized office building scenarios

Besides the site-specific building model described above, a generalized building model (GBM) is implemented with the same dimension, floor numbers and approximately the same number of rooms per floor. The floor plan of the generalized office building model as illustrated in Fig. B.3. The building layout is adopted from the instruction to the indoor office scenario by [103]. The path loss model is adopted from [103] A1 indoor office scenario. Case 2 of Non-Line of Sight (NLOS) is assumed for corridor to office room path loss calculation. The generalized office building model is used to verify the pervasiveness of the simulation results obtained in the site-specific model. Users are randomly distributed within the area of the whole building. The probability that a user occurs at any certain location is equal, which results in a uniform distribution of indoor users. The outdoor-to-indoor signal penetrated inside the building has an average strength of -143dBm per Hz.

### B.1.3 Placement of APs

In the enterprise scenario, the location of APs can be pre-planned so that each will cover a certain area. The performance of increased AP density is evaluated in the simulation. In the office scenario, the total number of APs under investigation ranges from 1 to 6 APs. Possible locations of APs are shown in Fig. B.4. The positioning of APs depends on the in-building AP number. Table B.1 gives the AP placement for different numbers of APs used in the simulation. The placements of APs will also have influence on the system performance. For example, with a total of 6 APs, the APs are located aligned on each floor. It is expected that such a way of AP placement can achieve the best performance in multi-cell scenarios. An optional AP placement strategy is that the APs are placed interleaved between different floors.

Another AP placement scenario is simulated: the non-optimal placement, as opposed to the planned placement illustrated in Fig. B.4. The location of the installed

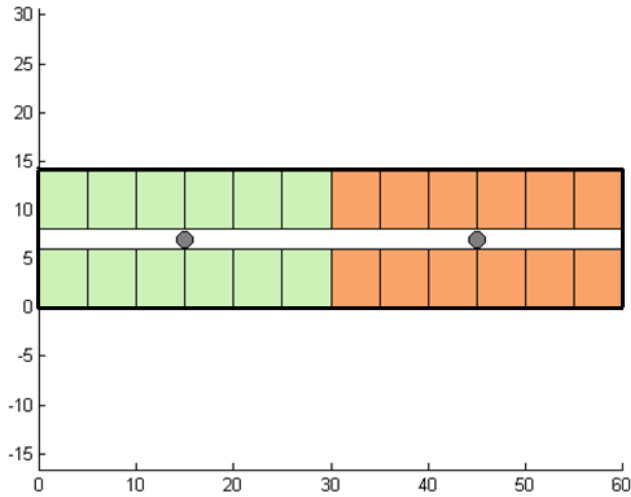


Figure B.3: Floor plan of generalized office building model.

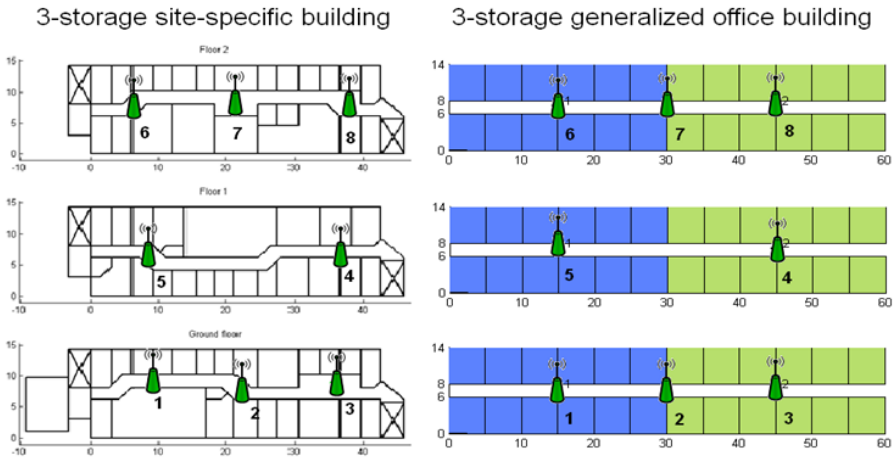


Figure B.4: Possible access point locations in-building.

indoor APs are affected by many factors, among others are possibly the insufficient radio planning, availability of power supply or backhaul connection, hazard areas difficult for installing, etc. Sometimes they lead to a non-optimal placement of APs. This scenario is used to test the sensitivity of the indoor systems against AP placement. The placement of the non-optimally installed APs is illustrated in Fig. B.5.

Table B.1: AP locations for different number of APs.

In-building AP number	Location index
2	4,5
3	1,4,6
4	2,4,5,7
6	1,3,4,5,6,8

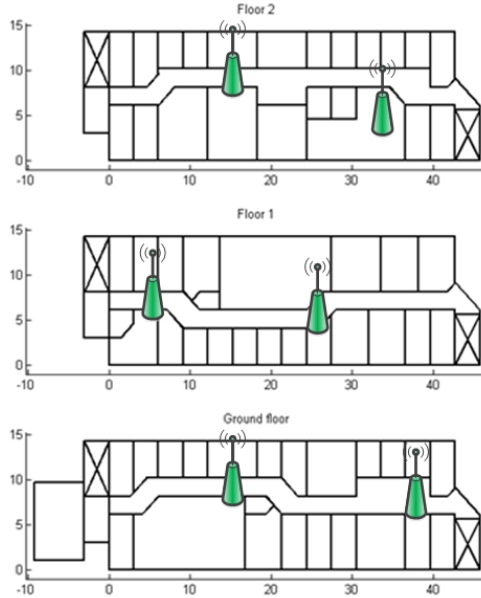


Figure B.5: Non-optimal placement of APs.

## B.2 General Assumptions of LTE in Full Buffer Traffic Simulations

Both full buffer and finite buffer traffic models are considered in the simulation, according to the guidelines in [37]. This section discusses the assumptions for the full buffer traffic used in this study.

For the full buffer traffic, UEs are active all the time, and different cell load can be achieved by varying the number of users per cell. Snapshot based simulations are performed for the system level performance evaluation. Base stations and UEs are generated for each snapshot. While UEs are randomly located, the placement of base stations (Femto cells or distributed antenna elements) may be either ran-

domized or pre-planned. A few thousands of snapshots are simulated to get the statistically averaged performance, and the throughput is collected from all these snapshots. Although not very realistic in many cases, the full buffer traffic is extensively used because of the simplicity.

The location of the building within the macro-cell network is also assumed to be random. The macro-layer is modeled according to the macro-cell case#1 as specified in [187]. It divides the network coverage area into many hexagonal sites, with 500 m inter-site-distance. Each site is further split into three sectors, served by a directional antenna. The 2-dimension antenna pattern is used for the macro-cells [187]:

$$A(\theta) = -\min \left[ 12 \left( \frac{\theta}{\theta_{3dB}} \right)^2, A_m \right] \tag{B.3}$$

where  $-180 \leq \theta \leq 180$  degree,  $\theta_{3dB} = 70$  degree is the 3 dB beamwidth when the antenna gain is reduced to half the maximum value,  $A_m = 20$  dB is the maximum attenuation. The three-sector antenna pattern within each site is shown in Fig. B.6.

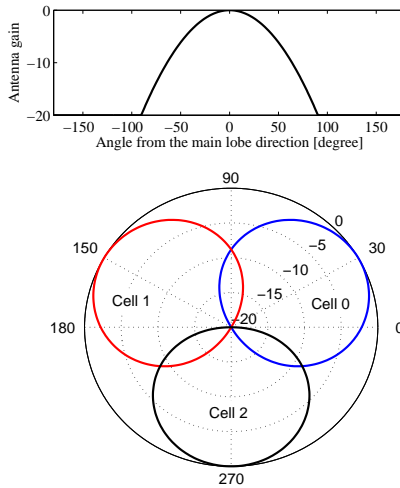


Figure B.6: The macro-cell 3-sector antenna pattern.

Table B.2 gives a short summary of the system assumptions for the full buffer traffic.



Table B.2: Parameters and assumptions for system level evaluation of in-building systems [37, 103].

Parameter	Setting/description
Spectrum allocation	20 MHz at 2.6 GHz
Duplexing scheme	FDD
Transmit power	Macro: 46 dBm; Femto and DAS: 20 dBm per antenna per access point; user: -30~24 dBm
Antenna gain	Macro: sectorized with 14 dBi gain; Femto and DAS: "Omni-directional" with 3 dBi; user: 0 dBi
Number of PRBs	50 (12 sub-carriers per PRB)
Receiver noise figure	9 dB
Cell selection	Users are always connected to the cell with the strongest received pilot signal
Scheduling awareness	Wideband Channel Quality Information (CQI), average Channel quality
Minimum user throughput requirement	2 Mbps at 5% outage rate
<b>Generalized in-building model</b>	
Room size: $5 \times 5 \text{ m}^2$	
Corridor width	5 m
Indoor wall attenuation loss ( [103] A1)	Light wall: 5 dB; Thick wall: 10 dB
Indoor path loss ( [103] A1)	$\left\{ \begin{array}{l} \text{LOS: } 18.7\log_{10}d + 46.8 + 20\log_{10}(fc/5.0) \\ \text{NLOS: } 20\log_{10}d + 46.4 + n_w L_w + 20\log_{10}(fc/5.0) \\ \text{where} \\ d = \text{direct-line distance [m]} \\ f_c = \text{carrier frequency [GHz]} \\ n_w = \text{number of walls between transmitter and receiver} \\ L_w = \text{wall attenuation [dB]} \end{array} \right.$
Shadow fading	Uncorrelated, log-normal with 3 dB std.

### B.2.1 The Physical Layer Modeling

For the physical layer modeling of the simulator, we first calculate the ideal SINR value for each UE. This ideal SINR is calculated from the signal power, the interference power and the noise level. Afterwards, the hardware imperfection of Error Vector Magnitude (EVM) is taken into consideration [188]. A 3% value of EVM is assumed, which puts a maximum limitation on the received SINR of:

$$SINR_{max} = -20\log_{10}0.03 = 30.5\text{dB} \quad (\text{B.4})$$

The received SINR then becomes [189]:

$$SINR = 1 / (1/SINR_{ideal} + 1/SINR_{max}) \quad (B.5)$$

Afterwards, a SINR to spectral efficiency mapping is applied to abstract the detailed physical layer processes. The mapping function is modified from the Shannon's formula to approximate the performance of the LTE system. According to [163], the capacity in a SISO LTE system can be estimated by:

$$S = \min \{ \beta \cdot \log_2(1 + \text{frac} SINR \alpha), 5.02 \} \quad (B.6)$$

where  $S$  is the estimated spectral efficiency in bps/Hz, which is upper limited according to the hard spectral efficiency given by 64-Quadrature Amplitude Modulation (QAM) with the coding rate 9/10 (5.4 bps/Hz) and the cyclic prefix (0.93);  $\beta$  adjusts for the system bandwidth efficiency and  $\alpha$  adjusts for the SINR implementation efficiency.  $\{\beta, \alpha\}$  has the value of  $\{0.56, 2.0\}$  in the downlink, and  $\{0.52, 2.34\}$  in the uplink. Although (B.6) treats the interference as Gaussian, it has been shown in [163] to provide an accurate throughput estimation in a multi-cell system with non-Gaussian interference.

For a 2 by 2 MIMO system, the adaptation between MIMO diversity and MIMO multiplexing schemes is considered. This is achieved by having:

$$S = \begin{cases} \min \{ 0.56 * \log_2(1 + SINR), 5.02 \}, & \text{diversity} \\ \min \{ 0.65 * \log_2(1 + SINR/1.6), 10.04 \}, & \text{multiplexing} \end{cases} \quad (B.7)$$

The following KPIs are used for the evaluation of the system performance:

**Average cell throughput:** the cell throughput averaged over all simulated cells.

**Cell edge user throughput:** the 5% worst UE throughput from all simulated ones.

**Outage probability:** the percentage of UEs who do not fulfill the minimum throughput requirement.

**Number of required APs:** the minimum number of APs (Femto cells or distributed antenna elements) that is required to satisfy the QoS requirement.

## B.3 General Assumptions of LTE in Finite Buffer Traffic Simulations

A more detailed physical layer model is employed for the finite buffer traffic model. It includes explicit modeling of e.g. link adaptation, HARQ and channel feedback.

The simulation parameters in addition to those for the full buffer traffic are summarized in Table B.3. The detailed assumptions are discussed in the remainder of this section.

Table B.3: Additional parameters and assumptions for finite buffer traffic.

Parameter	Setting/description
Arrival model	Poisson arrival with various arrival rates
Buffer size	2 Mbits
Admission control constraint	Maximum 50 users per cell
<b>More detailed physical layer model</b>	
Subframe duration	1 ms (11 data symbols plus 3 control symbols)
Modulation and coding	QPSK (1/5, 1/4, 1/3, 2/5, 1/2, 3/5, 2/3, 3/4), 16-QAM (2/5, 9/20, 1/2, 11/20, 3/5, 2/3, 3/4, 4/5, 5/6), 64-QAM (3/5, 5/8, 2/3, 17/24, 3/4, 4/5, 5/6, 7/8, 9/10)
1 <sup>st</sup> transmission BLER target	10%
HARQ modeling	Ideal Chase Combining with maximum 4 transmissions
CQI reporting	1 CQI per 3 PRBs; 1.6 dB quantization step; log-normal error with 1 dB std; 6 ms delay

### B.3.1 Link Adaptation

When Turbo decoder is used at the receiver side for the signal detection, its performance is sensitive with respect to channel variations. In general, a high level of Modulation and Coding Scheme (MCS) is more sensitive to the channel variation than a low MCS. We take a method called Exponential Effective SIR Mapping (EESM) [190] to model this imperfection. It calculates an effective SINR based on the individual SINR value within each PRB, according to

$$SINR = -\beta \ln \left( \frac{1}{N_u} \sum_{k=1}^{N_u} e^{-\frac{SINR_k}{\beta}} \right) \quad (\text{B.8})$$

In (B.8),  $\beta$  is the parameter obtained from link-level simulations to capture the decoder sensitivity for each MCS.  $N_u = 12$  is the number of sub-carriers within one PRB. The SINR value in (B.8) is also subject to EVM.

The LTE system supports three modulation levels for the data transmission, namely Quadrature Phase Shift Keying (QPSK), 16-QAM and 64-QAM. Together with turbo-coding, 26 MCSs in total have been considered. The SINR to Block

Error Rate (BLER) mapping for these MCSs is summarized in Fig. B.7(a), and their achievable spectral efficiency at different SINR values is shown in Fig. B.7(b). The Shannon bound and the performance with link adaptation are also plotted, assuming a BLER target of 10%. The SINR threshold and  $\beta$  value for EESM of each MCS is summarized in Table B.4, which is used in the system level simulation.

The specific curves are generated by using Turbo receiver in TU-20 channel, when each user is statically scheduled with 26 PRBs (312 sub-carriers), and coding is performed within these PRBs. According to the link level simulation, it is enough to achieve maximum interleaving gain by coding across these PRBs. For cases when a user is scheduled with less number of PRBs, this physical layer mapping is a bit optimistic. The accuracy in general is acceptable because the packet scheduler usually does not schedule more than 6 or 7 users in a 10 MHz bandwidth within each TTI.

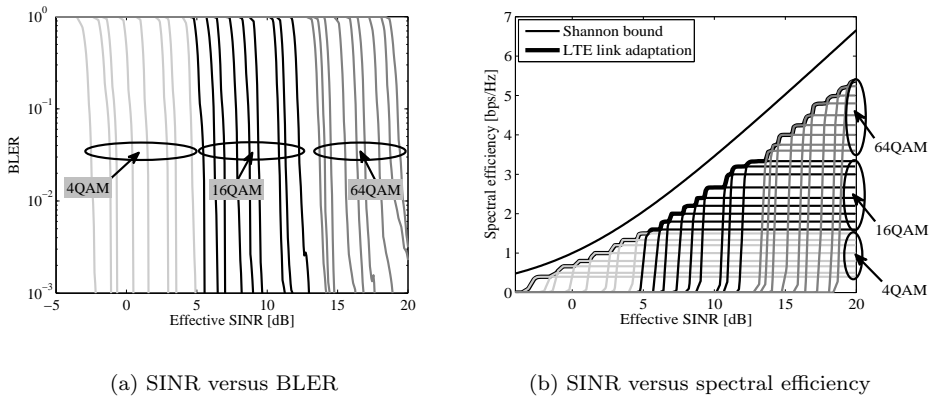


Figure B.7: Mapping from SINR to BLER and spectral efficiency.

Although link adaptation tries to select the MCS that fits the channel condition and the BLER target, it does not offer a guaranty of the achieved BLER. The uncertainty comes from many aspects, including the SINR estimation error, the feedback delay, inaccuracy due to quantization etc. In reality, the scenario and/or receiver characteristics may also be different from the reference case where the mapping table is generated. This will also lead to variations in the achievable BLER.

In order to stabilize the BLER at the targeting level, a viable approach is to use the Outer-Loop Link Adaptation (OLLA) [191, 192]. OLLA maintains an offset for each UE in each transmission direction (uplink or downlink), and updates it based on the packet detection output: if an Acknowledgement (ACK) is received,

Table B.4: Link to system level mapping table.

Modulation	Coding	Spectral Efficiency [bps/Hz]	10% BLER Threshold [dB]	EESM- $\beta$
QPSK	1/5	0.4	-2.7	1.34
	1/4	0.5	-1.3	1.57
	1/3	0.67	-0.8	1.44
	2/5	0.8	-0.2	1.52
	1/2	1.0	1.3	1.53
	3/5	1.2	2.7	1.58
	2/3	1.33	3.4	1.58
	3/4	1.5	4.6	1.69
16-QAM	2/5	1.6	5.3	4.33
	9/20	1.8	6.2	4.75
	1/2	2.0	6.8	5.25
	11/20	2.2	7.8	6.08
	3/5	2.4	8.7	6.64
	2/3	2.67	9.3	6.69
	3/4	3.0	10.7	7.45
	4/5	3.2	11.2	7.40
64-QAM	5/6	3.33	12.2	8.10
	3/5	3.6	13.6	21.25
	5/8	3.75	14.0	22.62
	2/3	4.0	14.5	22.91
	17/24	4.25	15.4	25.80
	3/4	4.5	16.3	28.74
	4/5	4.8	16.8	29.29
	5/6	5.0	17.8	31.07
7/8	5.25	18.6	33.15	
	9/10	5.4	19.2	33.78

the OLLA offset will be decreased by  $\Delta_{down}$  dB. Otherwise, it will be raised by  $\Delta_{up}$  dB. The relation between  $\Delta_{down}$  and  $\Delta_{down}$  is:

$$\Delta_{down} = \Delta_{up} \frac{BLER}{1 - BLER} \quad (B.9)$$

In this thesis, a step of 0.5 dB is taken for  $\Delta_{up}$ . With 10% BLER target,  $\Delta_{down} = 0.0556$  dB. The OLLA offset is also restricted within a range of -3~5 dB. During the link adaptation process, the OLLA offset is subtracted from the SINR value for selecting the proper MCS.

### B.3.2 Hybrid Automatic Repeat Request Management

HARQ ensures success packet reception at the receiver side by re-transmitting the previously failed packet. With sufficient number of re-transmissions and combination of the (re-)transmitted packets, very low packet drop ratio can be achieved. Asynchronous and adaptive HARQ is supported in LTE, which means that the re-transmission can be scheduled at any time on any PRBs. However, for the purpose of signal combining, the same MCS should be used. In this study, the Chase Combining is used. It exploits the MRC principle, and the output SINR is modeled as:

$$SINR_n = \epsilon^{n-1} \sum_{k=1}^n SINR_k \quad (\text{B.10})$$

In (B.10),  $SINR_k$  is the received SINR for the  $k^{th}$  (re-)transmission;  $SINR_n$  is the combined SINR after  $n$  transmissions, and  $\epsilon$  quantizes the combining efficiency. We model the HARQ process with the assumption of ideal Chase Combining ( $\epsilon = 1$ ) with up to 4 transmissions.

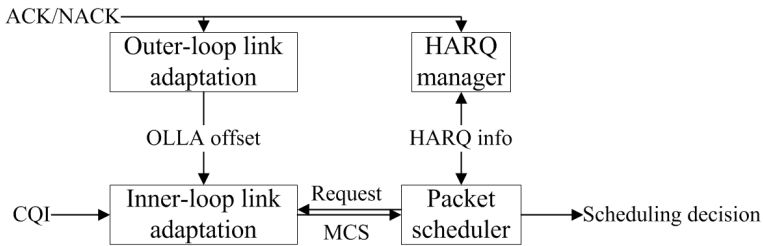


Figure B.8: Interaction between link adaptation, HARQ and packet scheduling.

Fig. B.8 summarizes the interaction between OLLA, Inner-Loop Link Adaptation (ILLA), HARQ management and packet scheduling. Here, ILLA is the conventional procedure of looking up the SINR-BLER table for selecting the proper MCS. This figure clearly shows how the ACK/Non-acknowledgement (NACK) information is used to adjust the OLLA offset, and in turn, the selection of MCS in ILLA. Finally, the output of the link adaptation function is used in packet scheduler for assigning resources to different UEs.

### B.3.3 Traffic arrival and departure model

The finite buffer traffic model is characterized by the fact that the users have a finite amount of data to transmit or receive. Between the two FTP traffic models specified in [37], we take the baseline model 1 in this study.

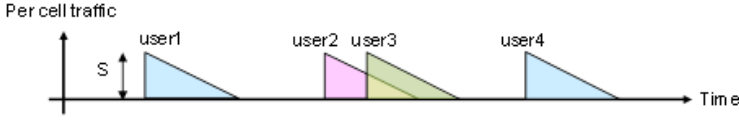


Figure B.9: Traffic generation of FTP Model 1 [37].

This FTP model is depicted in Fig. B.9 [37]. As shown in the figure, UEs are randomly generated in each cell at different times. The arrival of UEs follows a Poisson distribution with arrival rate  $\lambda_{arrival}$ . Each UE is associated with a fixed file to download (or upload). The file size is taken as 2 Mbits (0.5 MBytes). A UE will leave the system upon finishing the file transmission. This is also referred to as the ‘birth-death’ traffic model in the literature.

With the finite buffer traffic model, the cell load varies as time goes by, and hence a reasonably long simulation time is required to average out the load fluctuation. The time domain resolution used in the simulation is 1 ms, which corresponds to a TTI in LTE. Thus the average number of arrived UEs per cell per TTI is  $\lambda_{arrival}/1000$ . The probability of having  $k$  arrivals per TTI is:

$$Pr(X = k) = \frac{(\lambda_{arrival}/1000)^k e^{-\lambda_{arrival}/1000}}{k!} \quad (\text{B.11})$$

When  $(\lambda_{arrival}/1000 \ll 1, Pr(X \geq 2) \rightarrow 0$  and the Poisson distribution simplifies to a binomial distribution with  $Pr(X = 1) = \lambda_{arrival}/1000$ , and  $Pr(X = 0) = 1 - \lambda_{arrival}/1000$ .

A system is said to be ‘stable’ if the system is capable of serving all the arrived (offered) traffic load. In equation,

$$C_{system} \geq \lambda * S \quad (\text{B.12})$$

and

$$\lambda_{departure} = \lambda_{arrival} \quad (\text{B.13})$$

with  $S$  being the file size in Mbits,  $\lambda_{arrival}$  and  $\lambda_{departure}$  being the arrival and departure rate per cell per second.

If the system is unstable, UEs cannot get enough resources for their file transmissions. Admission control should be used to reject the UE arrivals, otherwise the arrived UEs at different time will accumulate in the system, resulting in heavy cell load and poor throughput per UE. With the finite buffer traffic model, it is possible to study the stability region (maximum supported offered load) of different wireless solutions, e.g. Femto and DAS system. Alternatively, for the same offered load, the minimum number of required Femto APs and DAS antenna elements can be found.

# Additional Simulation Results for Chapter 3

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In this appendix, we provide supplementary simulation results in complementary of those presented in Chapter 3. Section C.1 presents the 2-by-2 MIMO results for the equal-share scheduler; Section C.2 presents the 1-by-2 SIMO results for the quality-guarantee scheduler; and Section C.3 demonstrates the results obtained with the general building model to verify the overall conclusions we get with the site-specific building model used in Chapter 3.

## C.1 Simulation of Equal-share Scheduler with 2-by-2 MIMO

The results can be compared to those presented in Chapter 3 with 1-by-2 SIMO configuration and aligned conclusions can be drawn.



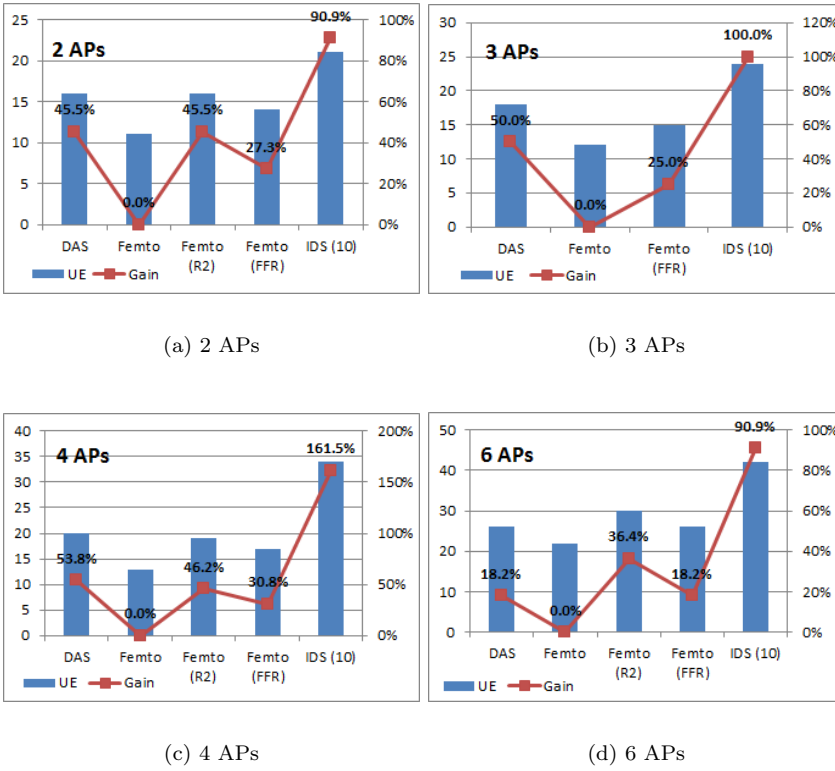


Figure C.1: Comparison of maximum simultaneously supportable number of QoS users of different systems according to different numbers of APs.



Figure C.2: Comparison of overall system throughput of different systems according to different numbers of APs.

## C.2 Simulation of QG Scheduler with 1-by-2 SIMO

The results can be compared to those presented in Chapter 3 with 2-by-2 MIMO configuration and aligned conclusions can be drawn.

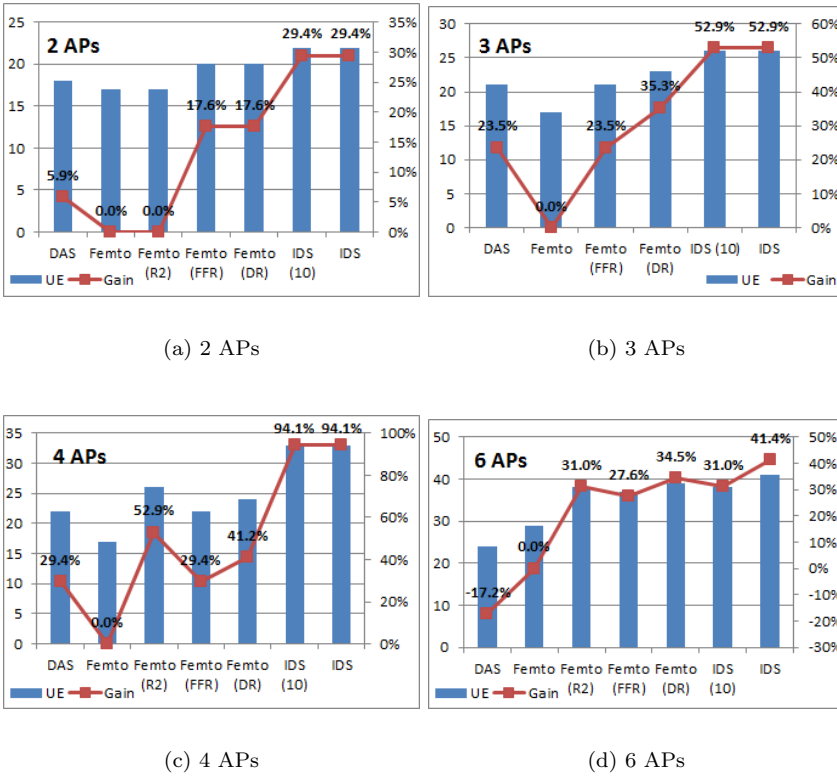


Figure C.3: Comparison of maximum simultaneously supportable number of QoS users of different systems according to different numbers of APs.

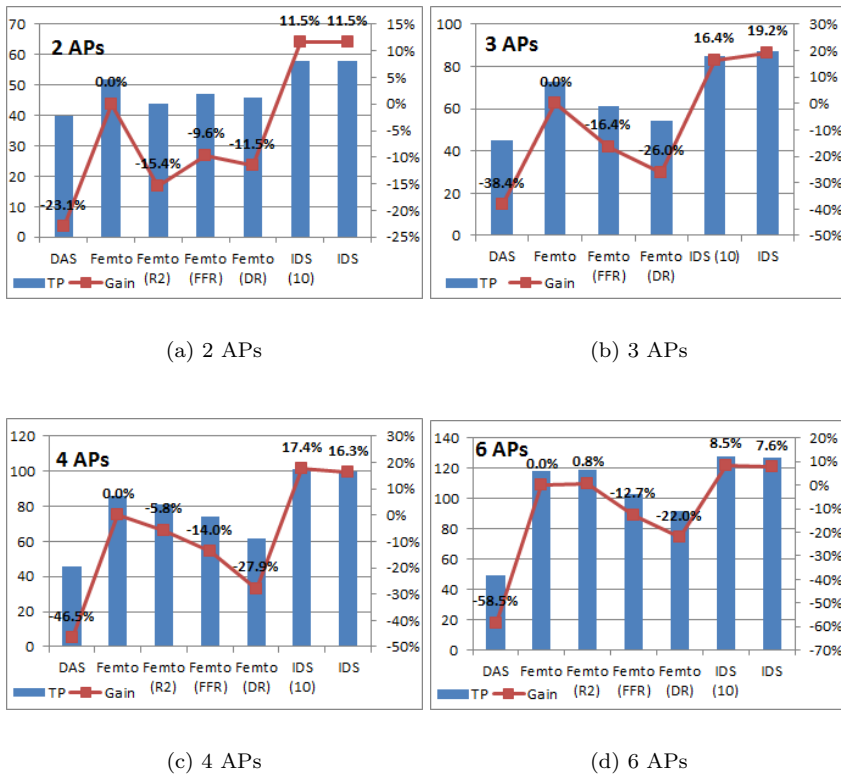


Figure C.4: Comparison of overall system throughput of different systems according to different numbers of APs.

### C.3 Simulation Using the General Building Model (2-by-2 MIMO)

The same trend is witnessed, which confirms our earlier observation except that the Femto reuse 2 system performance is more unstable in this scenario due to the irregular floor plan of the building model.

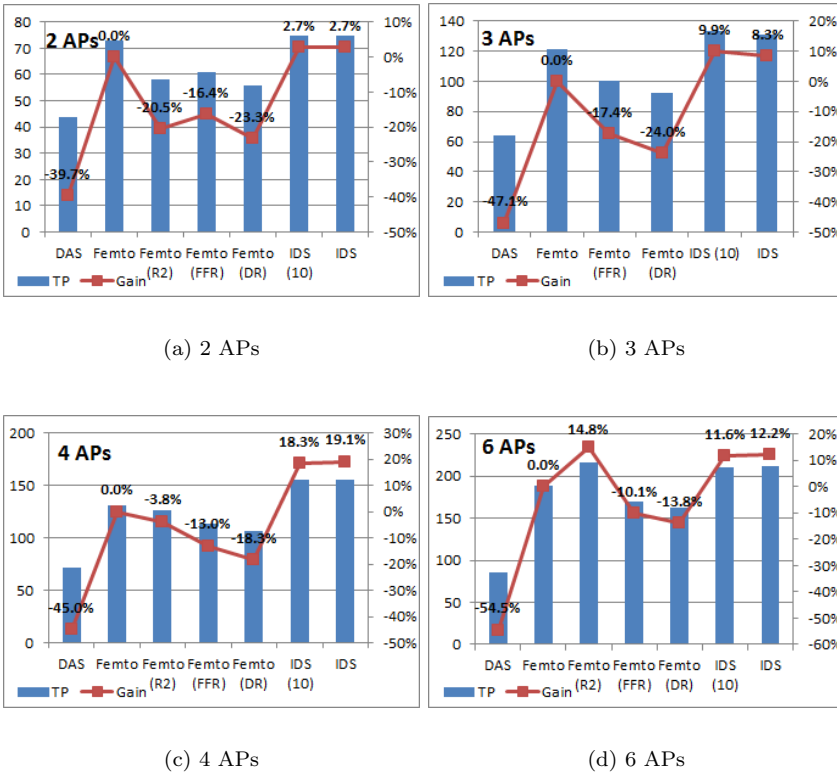
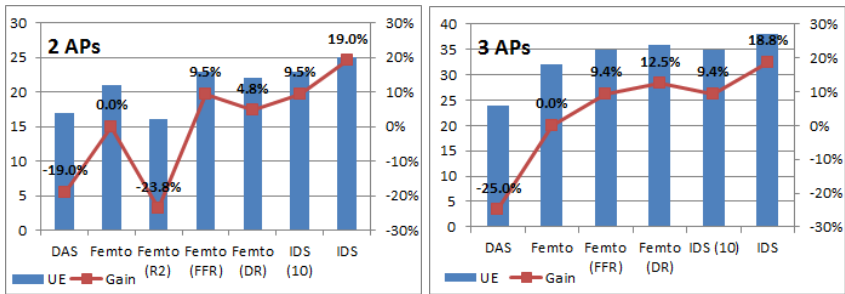
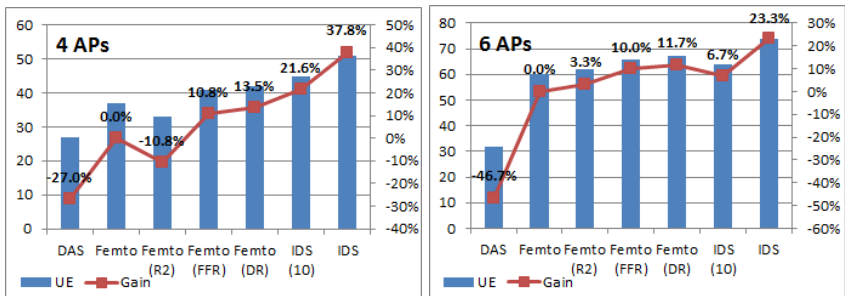


Figure C.5: Comparison of overall system throughput of different systems according to different numbers of APs.



(a) 2 APs

(b) 3 APs



(c) 4 APs

(d) 6 APs

Figure C.6: Comparison of maximum simultaneously supportable number of QoS users of different systems according to different numbers of APs.

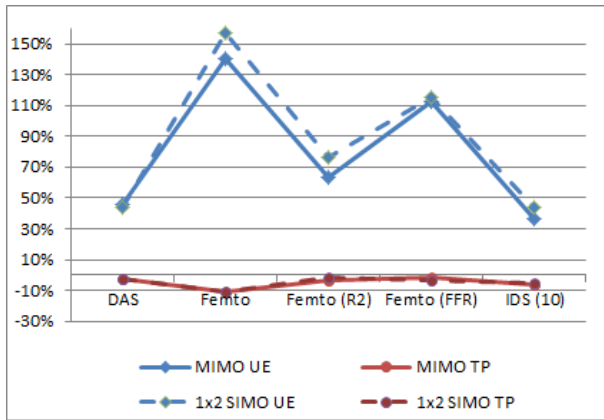
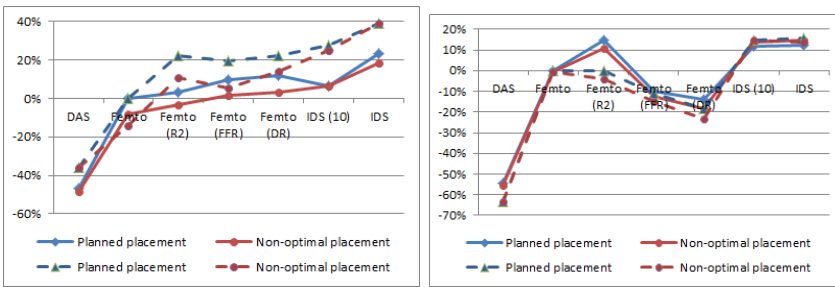


Figure C.7: Performance gain of using QG scheduler versus equal-share scheduler.



(a) Maximum supported UE

(b) System Throughput

Figure C.8: Performance degradation of maximum simultaneously supported QoS users and overall system throughput by non-optimal placement of 6 APs.

# Uplink Fractional Power Control

---

In the uplink transmission, power control is applied to minimize the interference as well as to prolong the user battery life [193]. The uplink fractional power control (FPC) mechanism contains both open-loop and closed-loop operations. Specifically, the open-loop component partially compensates for the path loss [194], whereas the closed-loop component offers adaptation to the channel quality variations [195–197].

$$P[\text{dBm}] = \max\{P_{\min}, \min\{P_{\max}, P_0 + \alpha * PL + 10 * \log_{10}M + \delta_{mcs} + f(\delta_i)\}\} \quad (\text{D.1})$$

- $P_{\max}$ : maximum UE transmit power in dBm
- $P_0$ : parameter composed of cell specific value and UE specific correction in dBm
- $\alpha$ : pathloss compensation factor
- $PL$ : path loss value between a UE and its serving AP in dB
- $M$ : number of PRBs scheduled for the UE
- $\delta_{mcs}$ : UE specific parameter related to selected MCS in dB



-  $f(\delta_i)$ : closed-loop correction factor in dB

The last part  $\delta_{mcs}$  and  $f(\delta_i)$  concerning closed-loop operations are not considered in this study.  $P_{max}$  is determined by user equipment transmit power limit;  $PL$  and  $M$  are determined by the channel measurement and instantaneous scheduling decision. The remaining two parameters,  $P_0$  and  $\alpha$ , are the tunable ones which we will examine in this section. Because the channel varies slowly in the indoor system, fractional path loss compensated power control is applied. The transmit power for a user is [193, 198]:

$$P = \max \{P_{min}, \min\{P_{max}, P_0 + \alpha PL\}\} \quad (\text{D.2})$$

where  $P_{min} = -30$  dBm,  $P_{max} = 24$  dBm.

Investigated by many previous works, a widely adopted  $\alpha$  value of 0.6 was found for the outdoor macro networks, while the optimum  $P_0$  value is around 50-60 dBm. For indoor environment, we investigate for the optimal  $[P_0, \alpha]$  settings by system simulation. The simulation is done by using the general building model described in Appendix B. Single antenna system (SISO) is assumed. As the goal is to investigate the impact of uplink FPC on the uplink performance, we eliminate the impact of other interference source by assuming no macro interference. There are a total of 30 users in the building, and the packet scheduler used is an equal-share scheduler.

## D.1 Performance in Reuse-One System

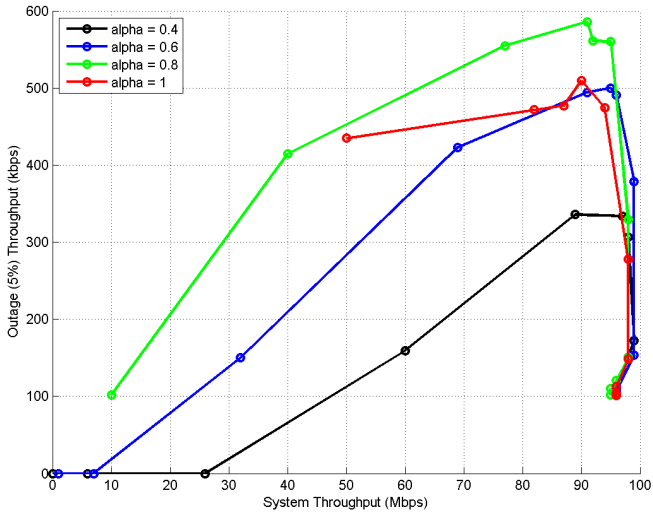
The reuse-one system as introduced for multi-Femto system in Chapter 2.3.2 is performance-limited by heavy inter-cell interference. The goal of applying FPC in the uplink is to minimize the uplink interference between different users. In the simulation, a series of  $\alpha$  value of [0.4, 0.6, 0.8, 1.0] was examined; and the value of  $P_0$  ranges from -100 dBm to 0 dBm with an interval of 10 dB. The smaller the  $\alpha$  value, the less compensation for the pathloss. As  $\alpha$  value approaches 0, the users will transmit at fixed power. When  $\alpha$  value increases to be close to 1, the cell edge users are transmitting at higher power than users at cell center, which helps them to improve their SINR condition. As to the parameter  $P_0$ , a too small value of  $P_0$  makes the system noise-limited as the received uplink power is too low. However, it should not be set too high, because then all UEs will start to transmit at full power and the compensation effect brought about by setting  $\alpha$  will be eliminated.

We can see from the result shown in Figure D.1 that, a combination of  $\alpha$  equals 0.8 and  $P_0$  equals -70 dBm gives the best performance. In general, a higher  $\alpha$

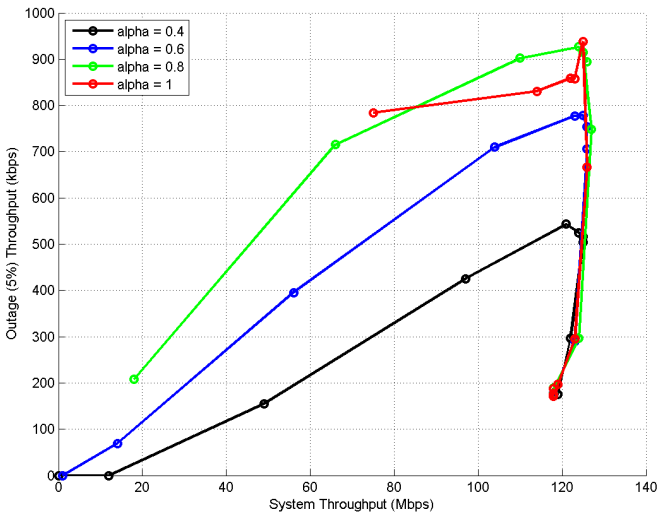
value results in better performance, which can be expected in the interference-limited scenario. When  $P_0$  is set to be higher than -40 dBm, the performance decreases sharply as more and more users tend to transmit at full power. In Chapter 3, the  $[\alpha, P_0]$  pair is set to be  $[0.8, -70]$  in the simulation evaluating the uplink performance of variant indoor systems.

## D.2 Performance in Reuse-Two System

For the reuse-two system (introduced in Chapter 2.3.2), the same simulation assumptions are applied as in section D.1. The results can be seen in Figure D.2. Both the 5% throughput and system throughput performance improves as the value of  $\alpha$  and  $P_0$  increases, which means that higher transmission power leads to better performance, and the performance is best when all users are transmitting at full power. So no power control is applied for the reuse-two system in the simulations in Chapter 3.

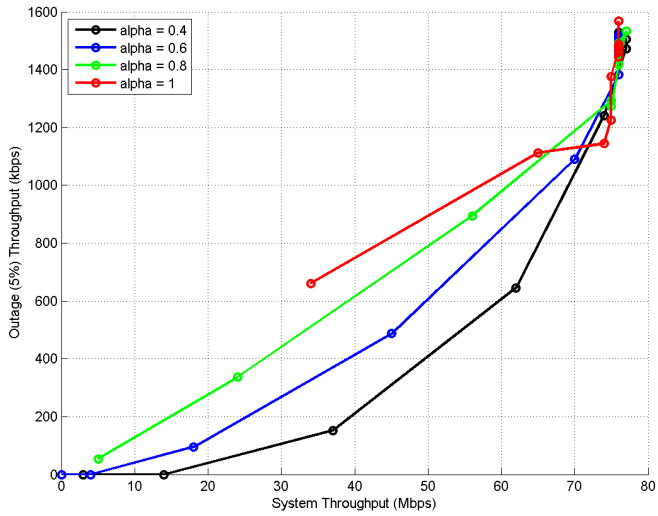


(a) 4 APs

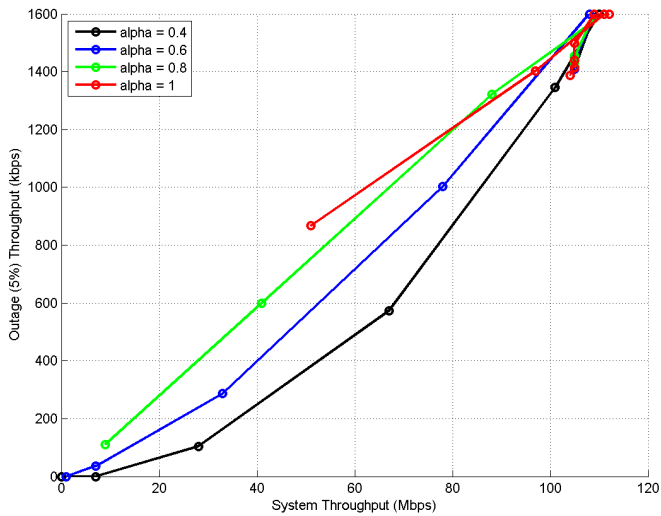


(b) 6 APs

Figure D.1: System performance as a function of variant  $\alpha$  and  $P_0$ .



(a) 4 APs



(b) 6 APs

Figure D.2: System performance as a function of variant  $\alpha$  and  $P_0$ .



# DAS Link Loss Calculation

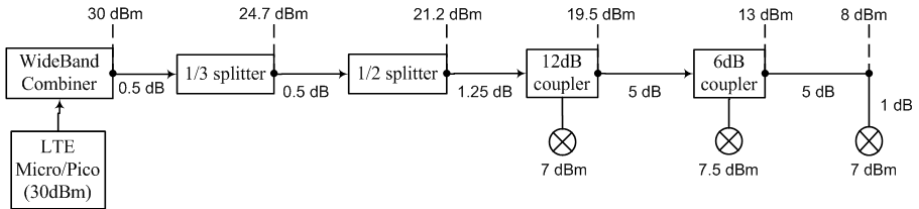


Figure E.1: DAS link loss calculation

The signal strength presented in Figure E.1 is a link loss estimation of a single path for the distributed antenna system illustrated in Figure 5.3. This also justifies the design of the DAS in Figure 5.3, because the remote antennas output at almost a unified power level of around 7dBm.

In the calculation, we assume 0 dB insertion loss for all the combiner and power splitters. The base station is connected to the wide-band combiner by a short (within several meters) optical fiber link, where 0dB of loss is assumed. The 7/8" co-axial cable is used for connecting the wide-band combiner and the two power splitters. With a short cable length of 10 meters, the 7/8" cable only gives a loss of 0.5dB. In the other places, the 1/2" co-axial cable is used. The cable loss of such a cable is assumed at 12.5 dB per hundred meter. Through a length of 40 meters, it reduces the signal strength by 5 dB.



## APPENDIX F

# Cost Assumptions and Price List

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- European market product quality equals Andrew and Kathrein
  - China local producer with very low price
  - Price of products that have variety of categories are subject to average
  - 5-year
- 
- Femto annual maintenance cost: 20% of CAPEX
  - Power bill of Femto access points are paid by building owner (similar as office WiFi)



Table F.1: DAS device and components.

Device name	Depreciation (year)	European Market (€)		China Market (€)	
		Product price	Service price (installation)	Product price	Service price (installation)
Power supply / backup system	20	600	72	300	36
Alarm system	10	500	60	250	30
AC/DC converter	10	440	55	220	27.5
AC/DC power cable	10	6.6	2.2	3.3	1.1
7/8"	20	6.4	2.4	3.2	1.2
7/8" connector	20	12.9	1.3	6.5	0.65
1/2"	20	4.5	1.9 <sup>1</sup>	2.3	0.95
1/2" connector	20	11.8	1.3	5.9	0.65
Fiber cable	20	11	1.32	5.5	6.6
Combiner / Splitter/ Divider	10	275	24.2	137	12.2
Coupler	10	80	22	40	11
Omni-directional antenna	10	28.6	24.2	14.3	12.1
Directional antenna	10	192	82.5	96	41.5

Table F.2: DAS OPEX.

Maintenance		
Annual cost	10% of CAPEX	
Electricity consumption		
Power (Watt)	Macro base station	1400
	Pico base station	120
Electricity price (€/kW/h)	European Market	0.15
	Chinese Market	0.06

Table F.3: Backhaul cost.

Fiber (Self-deployed)		
Price per link	European market	Chinese market
Digging fee (€/m)	100	4.5
Equipment cost (€)	3800	3800
OPEX (€/km/year)	1000	180
Microwave		
Price per link	European market	Chinese market
Equipment, antenna and cable (€)	11900 (8 years depreciation)	6000
Installation (€)	High-cost: 2800, Low-cost: 280	1000
Maintenance (relative to CAPEX)	7.5%	400/year
Spectrum license (€/month)	High-cost: 350, Low-cost: 175	50
Site-lease (€/month)	0	0



# TCO Analysis for Multi-operator Shared DAS

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The analysis presented in chapter 5 assumes that the indoor system facility is owned by a single mobile network operator, who pays for every cost of the whole project. However, one of the great advantages of the DAS is that its distributed infrastructure can be shared, not only by multiple radio techniques (GSM, CDMA, HSPA, LTE or WiMax), but also by multiple operators. In the latter case, the cost of building the distributed system can be split and shared among multiple operators. Therefore, the cost spent by each individual operator is much reduced, which makes the DAS a more appealing solution to use under many circumstances.

We examine the cost shared by one single operator who shares the same DAS facility with other operators, assuming that each operator has an equal share of cost on the common goods. The CAPEX, IMPEX and OPEX of the distributed system are shared among operators. The CAPEX, IMPEX and OPEX of the base station equipment and its supporting facilities (wall mounting kit or rack, power cable, battery backup, etc.) are paid by the individual operator. The TCO results as compared to the Femto system are presented in Figure G.1. We assume that there are three mobile operators sharing the DAS.

In the analysis presented in chapter 5, a newly built SISO DAS costs more than the Femto (low-cost) system when its per-sector coverage size is less than a large-size building, i.e. less than  $40.000\text{ m}^2$ . A newly built MIMO DAS always costs more than the Femto (low-cost) system regardless of the building size. Even the

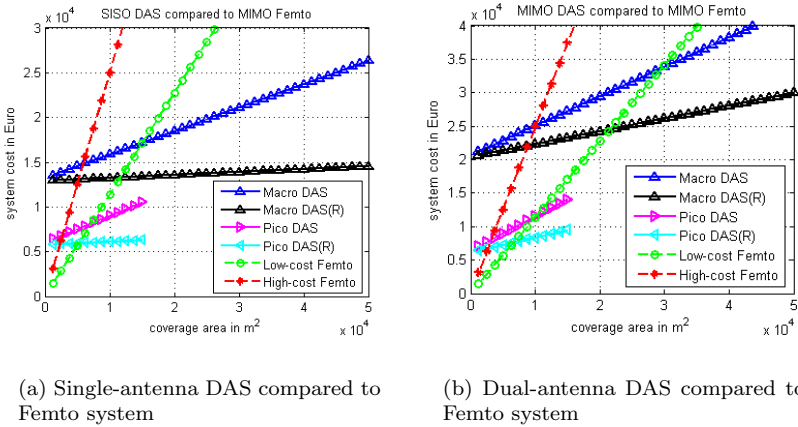


Figure G.1: TCO of indoor systems as a function of per-sector coverage size.

high-cost Femto system has a cost advantage over the DAS when the DAS's per sector coverage size is less than  $15,000 m^2$ . Comparing the previous results with those shown in Fig. G.1, we can see that sharing the DAS by multiple operators brings about great economical merit to the DAS. By sharing the DAS among three operators, even the MIMO DAS becomes more economical than the Femto system for medium-size and large-size buildings. The Femto system is only cheaper than the DAS when the building size is less than  $10,000 m^2$ . Furthermore, when the per-Femto CAPEX exceeds  $800 \text{ €}$  (the high-cost Femto), the Femto, compared to the DAS, loses its benefit for buildings of any size. Overall, we can see that sharing the same DAS facility among multiple operators is an efficient way to provide next generation indoor coverage at much reduced cost, and may in many scenarios be more economical than deploying Femto.

# List of Acronyms

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**1G** First Generation

**2G** Second Generation

**3G** Third Generation

**4G** Fourth Generation

**3GPP** Third Generation Partnership Project

**ACCS** Autonomous Component Carrier Selection

**ACK** Acknowledgement

**AP** Access Point

**BBU** Baseband Module/Unit

**BLER** Block Error Rate

**BS** Base Station

**BTS** Base Transceiver Station

**CAPEX** Capital Expenditure

**CATV** Cable TV

**CoMP** Coordinated Multi-Point

**CQI** Channel Quality Information

**CSMA/CA** Carrier Sense Multiple Access/Collision Avoidance

<b>CSG</b>	Closed Subscriber Group
<b>DAS</b>	Distributed Antenna System
<b>DCS</b>	Digital Cellular Service
<b>DPV</b>	Discrete Present Value
<b>DSL</b>	Digital Subscriber Line
<b>EDGE</b>	Enhanced Data rates for GSM Evolution
<b>EESM</b>	Exponential Effective SIR Mapping
<b>eNB</b>	enhanced NodeB
<b>EPC</b>	Evolved Packet Core
<b>EVM</b>	Error Vector Magnitude
<b>FAP</b>	Femto Access Point
<b>FDD</b>	Frequency Division Duplexing
<b>FPC</b>	Fractional Power Control
<b>GBR</b>	Guaranteed Bit Rate
<b>GPRS</b>	General Packet Radio Service
<b>GSM</b>	Global System for Mobile communication
<b>GW</b>	Gate Way
<b>HARQ</b>	Hybrid Automatic Repeat Request
<b>HeNB</b>	Home enhanced NodeB
<b>HetNet</b>	Heterogeneous Network
<b>HFR</b>	Hard Frequency Reuse
<b>HSPA</b>	High Speed Packet Access
<b>IBW</b>	In-building Wireless
<b>ICIC</b>	Inter-Cell Interference Coordination
<b>IDS</b>	Intelligent Distributed System
<b>IEEE</b>	Institute of Electrical and Electronics Engineers
<b>ILLA</b>	Inner-Loop Link Adaptation
<b>IMPEX</b>	Implementation Expenditure

- ISP** Internet Service Provider
- ITU** International Telecommunications Union
- KPI** Key Performance Indicator
- LIPA** Local IP Access
- LTE** Long Term Evolution
- MAC** Medium Access Control
- MCS** Modulation and Coding Scheme
- MIMO** Multiple Input Multiple Output
- MISO** Multiple Input Single Output
- MME** Mobility Management Entity
- MNO** Mobile Network Operator
- MRC** Maximal Ratio Combining
- NACK** Non-acknowledgement
- NLOS** Non-Line of Sight
- OBSAI** Open Base Station Architecture Initiative
- OFDM** Orthogonal Frequency Division Multiplexing
- OLLA** Outer-Loop Link Adaptation
- OPEX** Operational Expenditure
- OSG** Open Subscriber Group
- PC** Personal Computer
- PLMN** Public Land Mobile Network
- PRB** Physical Resource Block
- PWS** Public Warning System
- QAM** Quadrature Amplitude Modulation
- QG** Quality-Guaranteed
- QoS** Quality of Service
- QPSK** Quadrature Phase Shift Keying
- RE** Range Extension



- RF** Radio Frequency
- RN** Relay Node
- RRM** Radio Resource Management
- RRH** Remote Radio Head
- RRU** Remote Radio Unit
- RSRP** Reference Signal Received Power
- SC** Single Cell
- SC** Selection Combining
- SIMO** Single Input Multiple Output
- SINR** Signal to Interference plus Noise Ratio
- SISO** Single Input Single Output
- SLA** Service Level Agreement
- SNR** Signal to Noise Ratio
- SON** Self-Organized Network
- TAC** Tracking Area Code
- TCO** total cost of ownership
- TDD** Time Division Duplexing
- TDPS** Time Domain Packet Scheduler
- TTI** Transmission Time Interval
- UE** User Equipment
- UMTS** Universal Mobile Telecommunications System
- USB** Universal Serial Bus
- VoIP** voice over IP
- WCDMA** Wideband Code Division Multiple Access
- WiMAX** Worldwide Interoperability for Microwave Access

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