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Identification of femtocells in mobile networks

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Declaration

I hereby submit for the evaluation and defence the dissertation thesis elaborated at the Czech Technical University in Prague, Faculty of Electrical Engineering. I declare I have accomplished my final thesis by myself and I have named all the sources used in accordance with the Guideline on ethical preparation of university final theses.

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Marek Sedláček

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Abstract

The evolving mobile networks are requested to convey increasing data traffic as popularity of online services together with affordability of mobile devices is growing. One solution to mobile carriers, which can help them quickly deploy small base stations (BS) ensuring great indoor coverage with minimum costs, and high data rate capability, is femtocell technology. However, standard deployment techniques are unsatisfactory for these type of BSs. There are two main reasons for that. Firstly, femtocells will be deployed in great numbers. Secondly, they are deployed by users and are portable. It means their position is not known in advance, and can vary in time. Therefore, femtocells have to implement self-configuration principles. Physical Cell Identity is one of the most important parameters to be chosen automatically under defined conditions. It is crucial parameter, which allows them to convey a communication between a user equipment and a core network. A study on Physical Cell Identity issues in mobile networks with femtocells is presented in my thesis. For this purpose, I created two different models of femtocells deployment and deal with a collision and a confusion. They are two main problems, which threaten proper Physical Cell Identity assignment in mobile networks. Outputs of the thesis serves for better understanding of interrelations between differently placed femtocells in term of collision and confusion issue and as the basis to design the framework handling Physical Cell Identity allocation. The simulations conducted on proposed models were utilized to obtain probability characteristics and indicators based on graph theory. In the evaluation section, I appoint several characteristics as probability of collision, probability of confusion and maximal number of neighbourhood cells and some others to support solution of collision and confusion issue. I use results of evaluation and layout the framework for automated Physical Cell Identity assignment with two different approaches, the distributed one, and the centralized one. Since, femtocells are subcategory of small cells so findings, mentioned in this thesis, can also be used for other types of small cells.

Keywords: Femtocells, Small cells, Physical Cell Identity, Mobile networks, Identification, Collision, Confusion. 4G, LTE.

Abstrakt

Vzhledem ke skutečnosti, že objemy přenášených dat v mobilních sítích se neustále zvyšují, zejména díky vzrůstající popularitě online služeb a stále rostoucí dostupností mobilních zařízení, nastupující mobilní sítě se musejí s těmito nároky vyrovnat. Jedním z možných řešení je technologie femtobuněk, která operátorům umožní rychle a s minimálními náklady nasadit základnové stanice podporující vysokorychlostní datové přenosy, které efektivně řeší pokrytí vnitřních prostor budov. Avšak femtobuňky neumožňují zachovat současné principy aplikované pro budování základnových stanic, které spoléhaly na předem připravené plánování a statickou alokaci parametrů. Existují dva hlavní důvody, proč nelze uplatnit současný přístup. Prvním je skutečnost, že femtobuňky budou rozmisťovány ve velkých počtech. Druhým důvodem je jejich přenositelnost a zprovozňování samotnými uživateli, což znamená, že jejich poloha není předem určená a může se v čase měnit. Z toho důvodu je nutné začlenit řešení založená na samočinné konfiguraci. Fyzická identita buněk je jedním z hlavních parametrů, který se musí automatizovaně přiřazovat. Je to kritický parametr, jenž umožňuje femtobuňkám zprostředkovat komunikaci mezi uživatelským terminálem a páteřní sítí. V této práci je představena studie na problémy spojené s přiřazením fyzické identity buňky. Pro tyto účely jsem vytvořil dva modely rozmístění femtobuněk a zabýval se kolizí a konfuzí, dvěma hlavními problémy, jež jsou spojené přiřazováním fyzických identifikátorů buněk v mobilních sítích. Výstupy této práce slouží, k detailnějšímu pochopení vzájemných vztahů mezi femtobuňkami z hlediska kolize a konfuze a také jako základ pro návrh rámce řešícího automatizované přidělování fyzických identifikátorů buněk. Simulace provedené na navržených modelech byly využity pro vytvoření pravděpodobnostních charakteristik a získání indikátorů založených teorii grafů. V části zabývající se vyhodnocením simulací jsem stanovil několik charakteristik, které pomohou s řešením kolize a konfuze, jako například pravděpodobnost kolize, pravděpodobnost konfuze, maximální počet sousedních buněk a další. Na základě stanovených ukazatelů získaných z provedených simulací jsem navrhl rámec, který umožnuje flexibilně řešit automatizované přidělování fyzických identifikátorů buněk a to na základě dvou různých přístupů, distribuovaného a centralizovaného. Poznatky této práce mohou být také využity pro ostatní typy malých buněk, tzv. Small Cells, jelikož femtobuňky jsou jedna z jejich podkategorií.

Klíčová slova: Femtobuňky, Malé buňky, Fyzický identifikátor buňky, Mobilní sítě, Identifikace, Kolize, Konfuze, 4G, LTE.

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1 Introduction

The mobile networks have gone through rapid evolvement past the last fourth decades. The epoch of mobile networks dates to 1980. That time, first generation (1G) systems, as Nordic Mobile Telephony (NMT) or Advanced Mobile Phone System (AMPS), come into existence. They were analogue systems limited to voice services only. Second-generation (2G) systems as Global System for Mobile Communication (GSM), Code Division Multiple Access (CDMA) also known as Interim Standard 95 (IS-95) brought transition from analogue to digital technology. Second generation added to voice services data transmissions, but in very restricted form, e.g. High-Speed Circuit Switched Data (HSCD) supported data-rates 14.4 kbps per time-slot. Later phases of 2G systems offered higher data-rates, for example, General Packet Radio Service (GPRS) or Enhanced Data Rates for Global Evolution (EDGE) in GSM networks. They still provided rates sufficient only to text-based services.

Latterly, International Telecommunication Union (ITU) produced manifest International Mobile Telecommunications for the year 2000 (IMT-2000) focused to specify requirements for third-generation (3G) systems and it became clear that high-speed data-transfers have major role in future development. Creation of Universal Mobile Telecommunication System (UMTS) was reaction to such demands. Along with it, several new Radio Access Technologies (RAT) emerged, e.g. Wideband Code Division Multiple Access (W-CDMA) and High Speed Packet Access (HSPA). They have been created to accommodate such requirements on mobile networks. Therefore, 3G mobile networks onwards focus on high-speed data transfers. The main Standard Development Organizations (SDO), dealing with publishing specifications and organizing research activities, are Third Generation Partnership Project (3GPP) in Europe and 3GPP2 in America. The 3GPP publishes recommendations in so-called Releases (Rel.). Releases separate particular evolution phases and each release bring major or minor enhancements to existing technology. [1]

The 3G started with Rel. 1999 and after it, the 3GPP has imposed new numbering plan. Thus, the next release was Rel. 4 and this schema continues up to now [2]. In Rel. 5, the convergence of mobile network-core to all-IP network began, as IP Multimedia Subsystem (IMS) was standardised [3]. The IMS provides seamless support to deliver services to end-users independently on the type of network and device [4]. Rel. 8 brings specification for new radio access technology called Long Term Evolution (LTE) and a concept of new type BSs called Home Node B (HNB) [5]. Enhanced version of HeNB for LTE networks termed as Home

Evolved Node B (HeNB) came in Rel. 9, which brings capability to offload core network up to 90 % with Local Access Traffic Offload (LATO) and Global Access Traffic Offload (GATO) methods [6]. At the same time, evolution of core network (CN) began. The 3GPP called it System Architecture Evolution (SAE).

The SAE simplifies a network structure and a main component of SAE is Evolved Packet Core (EPC). A CN with EPC is all-IP based and supports different access technologies [7]. There exists only a packet-switched domain in EPC contrary to UMTS where both packet switched and circuit switched domain are present. Circuit-switched services in EPC are supported through IMS. Since LTE access network is packet based without support for circuit switching, common in all of earlier systems, voice services has to be realized as Voice over IP (VoIP) calls. Therefore, the Voice over LTE (VoLTE) specification was created. It enables voice calling with optional video transfer in LTE networks [8]. Another option to voice in LTE is Circuit Switched Fallback (CSFB), which disconnects User Equipment (UE) from LTE and enforces reconnecting to 2G or 3G network with support of circuit switched services [9]. Voice over Wi-Fi (VoWi-Fi) is another method to transfer voice in form of packets in LTE. VoWi-Fi has undoubted advantage of providing voice services even in places not covered by a mobile signal and is complementary option to VoLTE [10].

The Rel. 10 – 12 introduces enhancement to LTE known as LTE Advanced (LTE-A). In 2009, 3GPP made formal submission to ITU proposing LTE-A as mobile system of fourth-generation (4G) since it fulfils requirements of International Mobile Telecommunication Advanced (IMT-Advanced) issued by ITU [11]. LTE-A has capability to aggregate for multiple carriers, which allows bandwidth expansion. Specification prescribes peak spectral efficiency for downlink to 15 bit/s/Hz, which implies theoretical downlink speed to 1.5 Gbps for 100MHz bandwidth [12]. Additionally, it incorporates cooperation with Wi-Fi networks and continues in developing concept of femtocells. Other main new features is Coordinated Multipoint (CoMP) transmissions, In-Device Co-Existence (IDC), Machine to Machine (M2M) communication, Heterogeneous networks (HetNet), and extension in Multiple Input Multiple Output (MIMO) techniques. The Rel.13 onwards is labelled as LTE-A Pro [13]. One important feature introduced in Rel. 13, except additional extensions to LTE-A, is LTE Unlicensed (LTE-U), which allows aggregation of secondary carriers also in unlicensed spectrum. LTE-U is perspective technology also to Device-to-Device (D2D) communication and can greatly contribute to increase overall network capacity when cooperate with Wi-Fi networks [14].

LTE-A is not the only one 4G technology for mobile networks. Two major competitors were Worldwide Interoperability for Microwave Access (WiMax) and Ultra Mobile Broadband (UMB). WiMax was standardised by Institute of Electrical and Electronics Engineers (IEEE) and has two variants fixed and mobile, defined in 802.16 and 802.16e standards. WiMax Phase 2 directly competed with LTE to be 4G technology for radio access networks, but despite their earlier standardization, mobile operators choose LTE as primary technology [15]. The same case is UMB technology proposed by 3GPP2 as successor of Code Division Multiple Access 2000 (CDMA2000), as well as WiMax, development of UMB was terminated in favour of LTE.

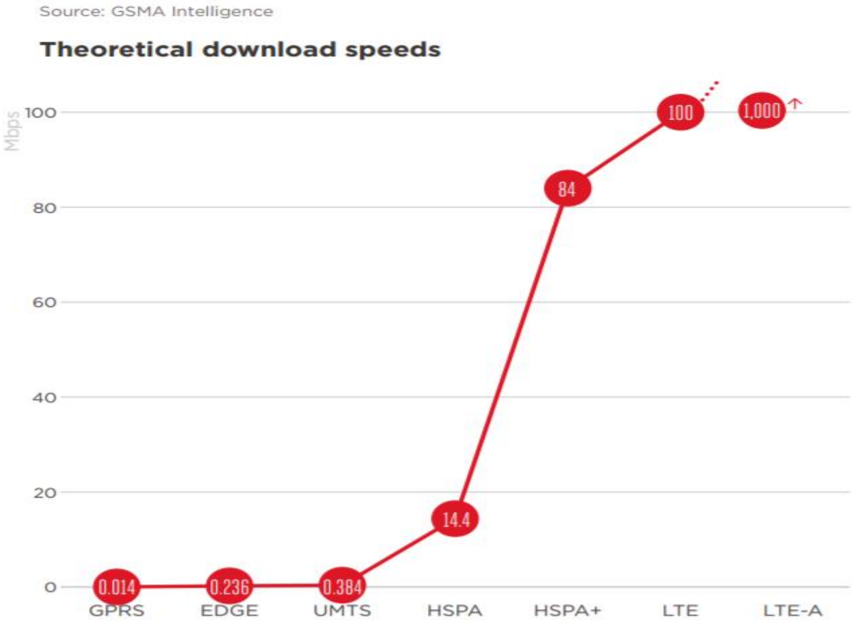

Figure 1.1 Theoretical data-rates by different Radio Access Technology. (Source [16])

Nevertheless, the research still continues and requirements for fifth-generation (5G) is well-specified and many proposals for it exists, despite the fact that 4G technologies still are not widely deployed, especially in Europe. Concepts of 5G networks are aimed to provide extreme data-rates with targeted speed up to 10 Gbps, enable cloud-mobile networking, infrastructure sharing, Virtualize Networks Functions (VNF), support of massive capacity, effective management through Software-Defined Mobile Networking (SDMN), and enable cell densification. Proposal for effective VNF infrastructure already exists [17]. Networks of fifth-generation become more user centric, not cell centric and new clustering techniques will help to improve overall performance [18]. These allow reduction of costs and provide entirely new level of flexibility. There is also anticipation of utilization of frequency bands above 6 GHz

[19]. Research activities on 5Gs are conducted in the framework of 3GPP proceedings under a term New Service and Markets Technology Enablers (SMARTER), which outlines future of development of mobile networks. In 2016, 3GPP roll out four SMARTER papers focusing on Massive Internet of things (IoT), Enhanced broadband, Critical communication, and Network operations [20].

A big challenge for 5G is to handle incorporation of new type of traffic as Vehicular to Anything (V2X), IoT and eHealth. Tactile internet, autonomous vehicles, and smart cities also create big opportunity to commercialization of 5Gs [21]. Virtual small cells (VCS) are another promising concept for 5G. VCS are based on massive antenna arrays with capabilities to deliver directional beam on a demand [22]. The manifest IMT for 2020 and beyond published by ITU also routes workings on 5G and shapes visions for future technologies of mobile systems after year 2020 [23]. The 3GPP anticipate fulfilment of IMT-2020 around 2019 within release number 16 [24].

Other organizations participating on development of mobile network industry toward 5G are Next Generation Mobile Network Alliance (NGMNA), Small Cells Forum (SCF) formerly known as Femto Forum, Broadband Forum (BBF), Wi-Fi Alliance (WA), and Internet Engineering Task Force (IETF). They all cooperate on research for evolution of mobile networks and make activities in marketing these new technologies.

The future of communication networks leads to Fixed Mobile Convergence (FMC). The goal of this is to make transparent using of wireless and fixed networks as one entity. The handover from fixed to wireless networks or contrariwise should be seamless and unnoticeable for users, who should not care about how they are connected. FMC enables to exploit full potential of both networks, mainly great capacity of fixed optic networks and mobility provided by wireless networks. Cooperation in the FMC framework is especially between 3GPP and BBF, which released basic definition of interworking functions in [25] – [26]. BBF and 3GPP works both on convergence on control pane and user pane. In context of 5G networks, it can be expected new level of convergence, designated as Convergence 2.0 because VNF allow new strategies in a network design [27]. The current RATs as LTE are able to facilitate transmissions with peak data rates about several hundreds of megabits per second, therefore in term of FMC they should be combined with corresponding technology on fixed network side. Passive Optical Networks (PON) is considered as most suitable and some concepts show how FMC between LTE and PON networks can be achieved in [28].

1.1 Basic concepts

A basic design principle of mobile networks, applied from 1G to the present, is a cellular structure. It means a whole network divides into smaller areas – cells. A network planner usually manages cells deployment, their size, and location. However, this concept of deployment is not always true for emerging networks and new technologies introduced in recent years. There, new types of cells, which have to be treated differently, are featured. The term cell is closely connected with a BS, which is a radio tower creating coverage on a site by emitting radio signal. Coverage is defined by directional characteristics of antennas on BS. Most often, a BS divides coverage of a site into three sectors of 120° each, and a cell is one its sectors. The cellular principle is applied to a network structure due to technological difficulties and even impossibility to have it all covered by only one cell. Such design enables flexibility in planning and deploying networks. In term of functions, general purposes of cells remain the same through all generations of mobile networks. They ensure mobility of users and scheduled quality of services (QoS). The exact form and set of functions incorporated into cells is changing vastly as mobile networks evolve. Thus, cell is important term with common features through all generations but with different specific natures in each evolution phase.

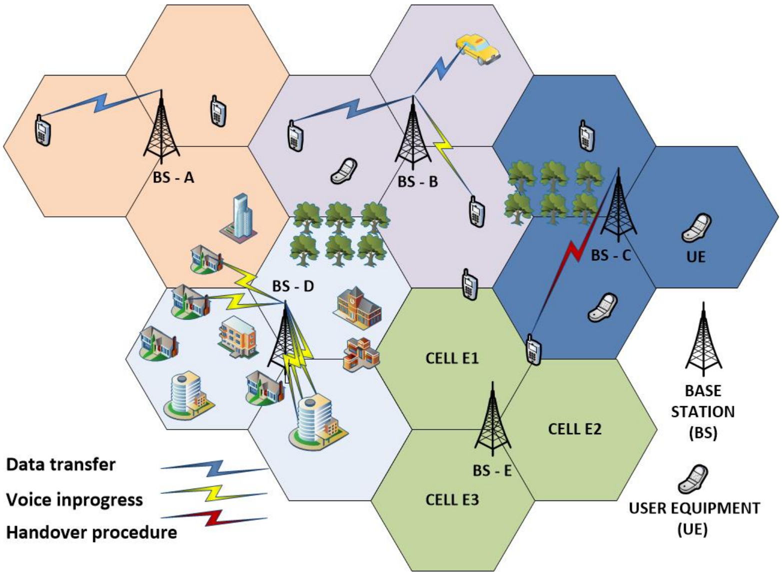

Figure 1.2 Cellular principle.

Macrocells are main type of cells for deployment of a mobile network. They are large, high-powered BSs and their radius of coverage can be up to several kilometres. Smaller areas are served by different types of base stations. Their purpose is especially to improve a capacity and a coverage in specific locations. These low powered BSs are called small cells, which is collective name for micro, pico, and femtocells. Small cells provide greater flexibility in a network design than macrocells. Sometimes they can be not only the less expensive variant to better services but also only possible solution. For example, deployment of an additional macrocell in a highly populated area can be impossible due to space requirements.

1.2 Heterogeneous networks (HetNet)

HetNet is a macrocell network combined together with small cells. Possibly, there can be another type of devices as Remote Radio Head (RRH), Wi-Fi access points, and Distributed Antenna Systems (DAS), but I do not mention them, because this paper aims mainly to femtocells, which is subcategory of small cells. HetNet with small cells helps to offload traffic from a macrocell backbone network, to increase a capacity in specific areas with high-loading [29]. Adding to that, small cells can greatly reduce poor reception at indoor locations and at edge of a macrocell [30]. However, introducing small cells into macrocell networks brings new challenges. Mainly, there are problems with interference on downlink (DL) and uplink (UL), because area of the strongest signal on DL does not coincide with equal path loss for UL, which applies for homogenous networks. In term of interference, there is important milestone Rel.10, which enable carrier aggregation and it enable new ways of interference management in HetNets [31].

There is also issue with hand-over to small cells as there can be many candidates and selection of the proper one may be not trivial. Next picture illustrates an overview of basic HetNet architecture.

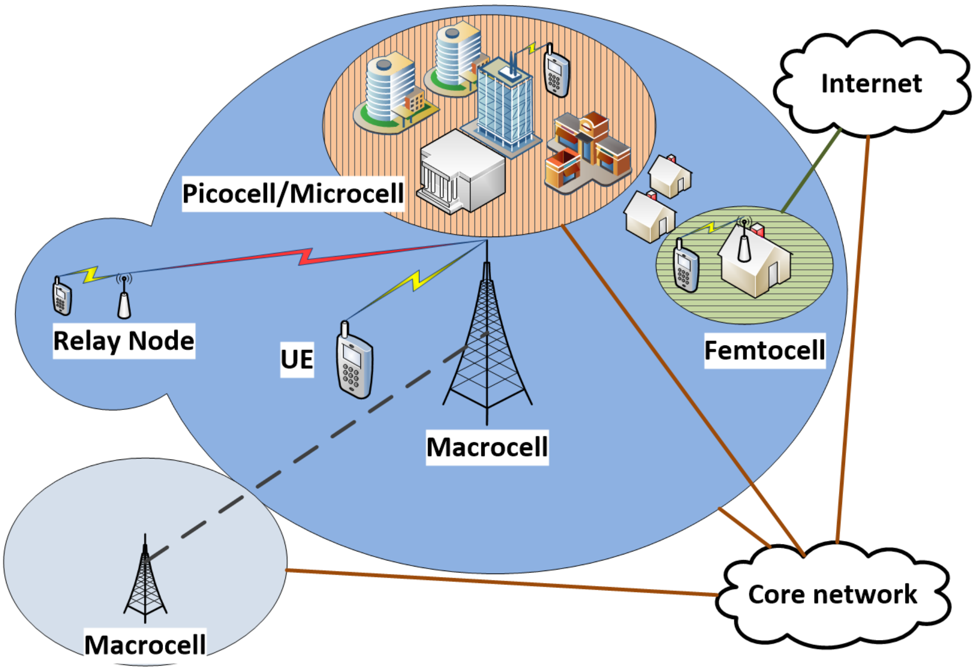

Figure 1.3 General overview on HetNet.

The picture is consisting of three layers also called tiers. A macrocell layer, the blue one, covers the largest area with several buildings. Coverage and performance of the macrocell is enhanced with a Relay Node (RN). Relay nodes, specified in Rel. 10, boost a capacity and a quality of signal at cell's edge. RN is managed by a macrocell, which is responding for Mobility Management Entity (MME) selection. The macrocell is referred as Donor eNB (DeNB) in such case. There are two types of RN according to 3GPP. RN of type 1 has the same in-band and out-band frequencies, contrary to a type 1a, which has them different [32]. The second tier is represented by picocells/microcells. These type of bases stations are intended to enterprise, rural or metropolitan deployment. The third layer makes up femtocells serving UE in residential areas. As small cells add separate tiers to a mobile network, there is need to manage not only co-tier issues but also cross-tier ones in HetNet. Management and design of HetNet is more complex due to these reasons.

1.3 Mobile telecommunication market

Market trends are undoubted factor driving evolution of mobile communications. Actually, they have direct influence on a direction of research activities. Thus, next development phases not only enhance technological aspects, but at the same time, they try to reduce costs of operating mobile networks, e.g. energy savings, better spectral efficiency etc.

Nowadays, mobile telecommunication market is mostly driven by smartphones. They have become available on a large scale and subscribers tend to use more and more data prior to voice services. Not only smartphones consume data but also other types of devices communicate over mobile networks as tablets and body-worn wearables. The number of 3G/4G subscriptions exceeded three billion in 2015 [33]. Finally yet importantly, IoT is next rapidly expanding sector, which means that not only users have to share a bandwidth of networks. According to GSM Alliance (GSMA), there will be 25.6 billion connected devices in 2020 [34]. These go along with growing popularity of cloud/web-based applications and online content streaming. Since the applications become independent to device, they can be accessed also from mobile terminals as handhelds, tablets, smartphones without many limitations imposed to them previously as different Central Processing Unit (CPU) architecture, operating systems, and hardware specifications, to name a few ones. All of these boost productivity together with volumes of data-transferred across networks [35]. Report Digital in 2016 showed that web traffic generated by mobile devices raised from 2.9 % in 2010 to 38.6 % in January of 2016 [36]. According to study presented by UMTS Forum data quantity sent out and received by mobile devices will be constantly boost. This forecast predicts that mobile traffic in 2020 will be 33 times larger than in 2010 [37]. Cisco states in its report that in 2015 the data traffic grew 74 % against previous year, average monthly mobile traffic counted around 3.7 exabytes contrary to 2.1 exabytes in 2014 and HetNets with small cells help to offload 51 % traffic through them [38]. Another important mention from Cisco showed that traffic generated from 4G networks exceed 3G traffic despite fact that 4G traffic resembles only 14 % of connections. It shows how big difference is between particular generations in term of data-rates. Therefore, todays networks have to able to deal with such skyrocketing demands on both volume and speed of data.

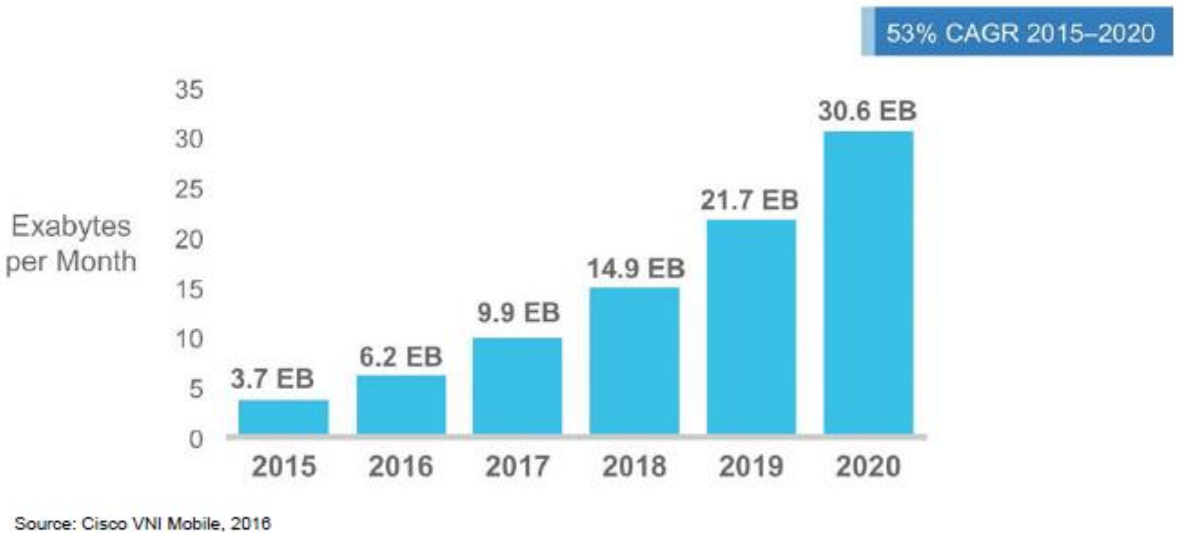

Figure 1.4 Cisco forecast of mobile data traffic by 2020 (Source [38])

However, time-delay has not to be ignored in favour of data-rates, because it is additional parameter greatly affecting user experience of online services, and as such, it has to be minimized whenever the application need time-sensitive transfers.

Data transfers are a big opportunity to mobile operators to increase revenues, because in the last few years Average Revenue per User (ARPU) still have decreased due to reduced outcomes from voice / SMS services [39].

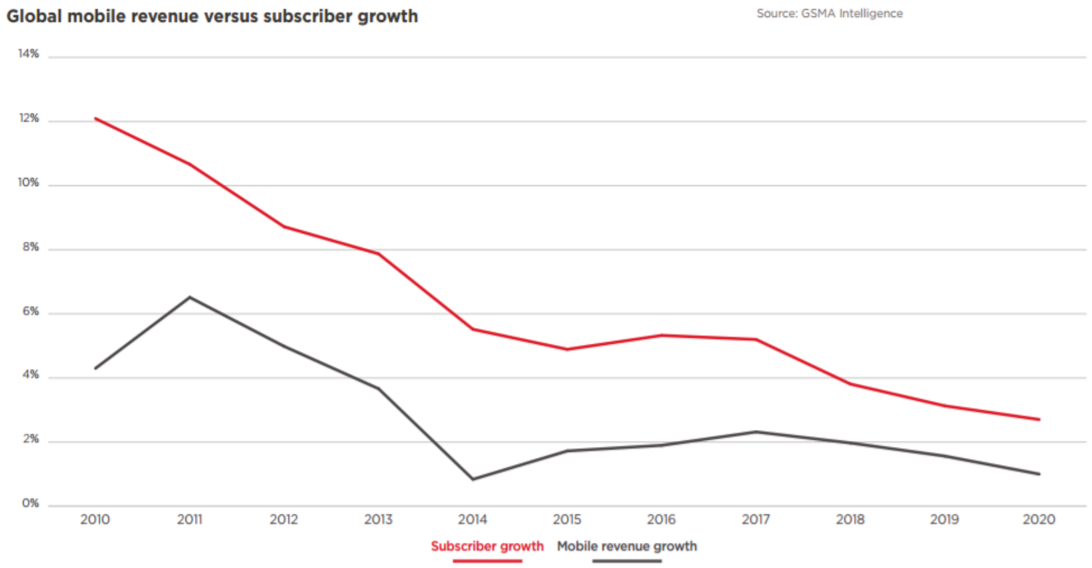

Figure 1.5 Trend of global mobile revenue vs subscriber growth. (Source [16])

Since, frequency bands are limited natural source, which is nearly exhausted on most usable frequencies, it is not possible to gross up capacity by extending bandwidth. Therefore, new technologies should aim to improving spectral efficiency. Better coding schemes and modulation are two of the possibilities to achieve it. They have greatly improved utilization of bandwidth recently from 0.047 b/s/Hz in W-CDMA up to present 15b/s/Hz in LTE. Thus, mobile operators can step up data-rates in their current licensed bands. The transfer to IP based CNs also help reduce expenditures as all technologies mobile and fixed are unified on a common protocol, which simplify interconnection.

1.4 Small cells enablers

The economic aspect is not only the main reason hindering growth of evolving networks. Radio signals conveying high-speed data-rates transmitted on higher frequencies (used by 3G, 4G systems) are more susceptible to obstacles. There are greater path loss caused by propagation and any obstructions (e.g. walls of buildings) even more attenuate the signal. Thus, it may happen to quality or throughput degradation inside buildings. Further, impaired reception may be expected for UE situated at cell's edge.

Therefore, for better QoS and full potential of high-speed date rates, it is important to have BSs as close as possible to UEs. The research of Ericsson shows we spent 90 % of life indoors [40], which coincides with statement that about 80 % of mobile traffic originates from indoor locations [41] and mobile consumption of data "on the move" is only 35 % according to Cisco [42]. Insufficient indoor coverage can cause issue and leads to call drops, especially in 4G networks [43]. As construction of additional macrocell BSs is not only cost-ineffective but also time-consuming, there is femtocell concept, which advertises solution of these issues. In 5G networks, there be will be strong insist to a capacity. A capacity can be enhanced by three techniques: extending frequency bands, increasing spectral efficiency, and adding more cells [44]. Since the first two techniques are limited, the third one seems most reasonable which support concept of small cells. They can be used to create ultra-dense networks that are one of the presumptions for 5G [45].

Recently introduced standard for embedded Subscriber Identity Module (eSIM), developed within the scope of GSMA, and mainly targeted to Machine Type Communication (MTC), can give an extra support to small cells expansion too. Since, an eSIM allows operators to manage subscriptions remotely in a device [46] and thus reduce costs.

The femtocells are also perspective technology for 5G networks because there is assumption of utilization of higher bandwidths, around 6GHz. Such frequencies are even more susceptible to obstacles in propagation. Hence, more cells will be needed to guarantee adequate signal quality. It can be anticipated that an optimal coverage in these bands will be strongly dependent on small cells.

A global survey conducted between service providers of mobile networks made by IHS Markit Company, shows that operator plan boots small cells deployment both in indoor and outdoor areas [47]. There is list of most relevant reasons for deploying small cells as viewed by participants of the survey.

- In-building capacity optimization
- Macro network asset sweating/offload
- Public venue capacity optimization
- Capex savings
- Non-expandability of macrocell network
- Optimization of high data usage areas
- Public venue coverage optimization
- In-building coverage optimization
- Footprint densification

1.5 Brief introduction to 3GPP System Architecture Evolved

General scheme of the System Architecture Evolved defined according latest 3GPP Release 14 [48] is shown on the next picture.

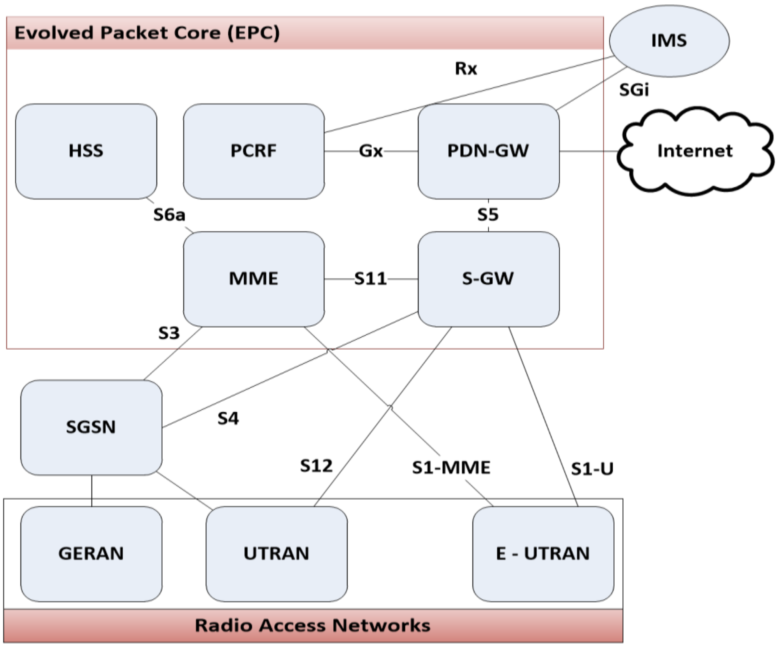

Figure 1.6 General overview of 3GPP architecture Release 14.

It consists of the Radio Access Network (RAN) where both legacy and current RATs can be found. Legacy RATs are the GSM EDGE Radio Access Network (GERAN) and the Universal Terrestrial Radio Access Network (UTRAN). The current state technology is the Evolved UTRAN (E-UTRAN) with LTE-A. The depicted architecture outlines versatility of the EPC as it can cooperate with whichever RAT. The EPC together with the E-UTRAN are referred as the Evolved Packet System (EPS). Main elements of the EPC are the MME, the Serving Gateway (S-GW), the Public Data Network Gateway (PDN-GW), the Policy and Charging Function (PCRF), and the Home Subscriber Server (HSS). Outside the EPC are the Serving GPRS Support Node (SGSN) and the IMS.

The MME is responsible for managing control pane between access and core network. The S-GW serves user pane functions. The PDN-GW interconnect mobile network with other IP networks. The HSS take care of storing information about users. The PCRF is responsible for monitoring of QoS, gating control, and charging according appropriate model [49].

1.6 Femtocell technology

The history of femtocells concept can be dated to 1999, when it became clear that a new type of BSs for improving indoor coverage is advisable. At that time, Alcatel brought in a GSM Home Base-Stations (GHBS), but as 2G systems mainly targeted voice services, use lower frequencies compared to 3G/4G, and expensive hardware of GHBS, it had no commercial potential. In 2007, the femtocell concept was revived for 3G systems, as need for better indoor coverage and capacity, has been more desirable with start of high-speed data [50]. There, the quality of mobile signal is determining factor to support data flows in order of several megabits per second. Until that time, signal quality was not of crucial importance, because voice transmissions are more tolerant to low or volatile quality of signal. For reference only, voice codec Adaptive Multi-Rate Wide-Band (AMR WB) standardised in Rel. 5 requires rates from 6.6 to 23.85 kbps [51].

In 2007, a consortium of more than 100 companies founded Femto Forum and development of the femtocells begin to pick up speed. Afterward, in 2012, Femtocell Forum renamed to Small Cell Forum. The main reasons of such change were to cover up broader spectre of technologies closely associated with femtocells and to reflect focus going beyond a home usage. SCF focus was extended to enterprise, urban, rural areas, and to coordinate development of these technologies having some set of common features [52]. The term of small cells comprises microcells, metrocells, and picocells, but femtocells are most important of them, as they are most challenging. Picocells contrary to femtocells can be deployed in the same manner as macrocells and main difference is smaller area of coverage. Metrocells and microcells cover proportionally wider area and they are proposed for smart cities concepts.

1.6.1 Basic overview

A femtocell, also known as Femto Access Point (FAP), is a low-powered BS operating in a licensed spectrum, installed inside buildings, and deployed on a customer premise as a Customer Premises Equipment (CPE). In terminology of 3GPP, femtocells are referred as Home Node B in UTRAN and Home evolved Node B (HeNB) in E-UTRAN. Since my thesis is focused on LTE/LTE-A networks, I use the term HeNB when speaking about technology specific properties and the term FAP or femtocell when referring to general features. Femtocells have presumed coverage range about 5 – 20 m and are able to serve about five users simultaneously [53]. In contrast to macrocells, femtocell uses customer’s broadband connection to backhaul to a CN of a mobile carrier. Connection via subscriber fixed line can be considered as a form of FMC.

A Femto Access Point could be installed to operate in a home, an office, or a public space (e.g. in shopping malls, coffee bars). According to deployment purpose, the 3GPP in Rel. 8 specifies three different access modes: closed, open, and hybrid [54]. Femtocells supporting Closed Subscribers Group (CSG) broadcast a CSG Identity, which permit access management of UE [55]. Closed access mode is suited for consumer sector, where only the registered UE is served by those cells. Additionally, it is possible to create CSG, where some set of UEs has access to cells (one or more cells) assigned to a group. Open mode offers public access for all UE in a serving area. Hybrid mode is trade-off between the two before mentioned. There some cell’s resources are reserved to registered UEs and the other may be advertised for every other device in a vicinity.

As a FAP is a CPE, mobile operators lose full-control and access to a femtocell. It means a FAP cannot be installed by trained technician but at the same time, it has to be ready to operate promptly. Moreover, deployment of femtocells differs from macrocells by the following factors: their location is not known in advance, they can unexpectedly disappear and emerge as user shut them off/on, they even can be moved by a subscriber to other location. All of these cause that sophisticated mechanism has to be employed to address such challenges. Therefore, there are efforts to automate setting tasks, which help mobile carriers to not only reduce operational expenditures (OPEX), but also enable them to create a network that quickly and flexibly reacts to actual demands. For that reason, a FAP has to be equipped with self-configuring, self-optimizing, and self-healing mechanism avoiding as much user input as possible [56]. Thus, femtocell networks should follow general principles defined for Self-Organized Network (SON) to achieve required level of automation. Nevertheless, self-configuration and self-optimization mechanisms have several radio related challenges need to solve as [57]:

- Coverage and capacity optimization
- Interference mitigation
- Mobility robustness and load balancing optimization,
- Automatic Neighbour Relation (ANR) function
- Automated configuration of Physical Cell Identity (PCI) allocation
- Synchronization
- Energy savings

In addition, security of femtocell networks has to be treated to provide robustness against networks attacks and to ensure protection of privacy.

1.6.2 Radio related challenges

Femtocells can pose a big challenge due their features as user installation, very limited coverage, high-density deployment, and different access modes. Thus, several issues have to be solved for seamless integration of femtocells into an existing network. Main issues are concerned mainly to handover and interferences, but the others, which may not be ignored, are mentioned in the text below.

Handover. A network with femtocells has to support several handover scenarios, handover from femto to macrocell referred as hand in, from macro to femtocell otherwise hand out, and among femtocells. The last type of handover may happen within the same gateway or between the different gateways. Sometimes, it may happen to unwanted short-time hand out from a femtocell to a macrocell and then immediately triggering hand in into the same FAP. It is caused by stronger Received Signal Strength (RSS) from a macrocell despite RSS from a femtocell can be still sufficient to serve a UE. These unwanted handovers leads to increased loading of macrocell and higher probability of call drops, especially in case of high density of FAPs in the area. Cell Range Extension (CRE) addresses the issue, but at the same time is source of higher interferences. CRE virtually extend coverage of a cell by adding an extra value to RSS. The value can be variable based on actual conditions [58]. CRE originally was proposed for traffic offloading from macrocells to picocells, but utilization in femtocell networks is possible.

Interference. Interference mitigation is important to increase overall system capacity and QoS. There are two strategies, centralized and distributed, to handle both cross and co-tier interferences. The centralized strategy consists of a central entity collecting information from an access network and sending a correct setting regarding to sub channels to each BS after data evaluation. The distributed approach, where each entity try to mitigate interference by own logic, is better suited for a femtocell networks, because high density of femtocells and their specific features. Additionally, it comes out that cooperative methods, where femtocells collaborate with nearest BSs, provide better results than non-cooperative ones [59]. Techniques used to reduce interference depend up to chosen frequency reuse pattern applied for deployment of a femtocell tier. Frequencies can be assigned the following manners:

- Orthogonal allocation
- Co-channel deployment
- Hybrid assignment

Orthogonal allocation means that each layer of a network, macrocellular and femtocellular, is assigned with different set of sub channels. It eliminates a cross-tier interference, but it decrements spectral efficiency and capacity of a particular tier. The second way, and the preferred one, is co-channel deployment, where each tier shares frequency bands. However, cross-tier interference has to be managed in such deployment. Hybrid assignment is combination of the previous two. Some sub channels are shared across tiers and some are dedicated. Generally, a dedicated spectrum used to be reserved for macrocells.

Co-tier interference can be managed by adaptive power control or switching of those cells, which do not handle any traffic. The mechanism also helps to reduce energy consumption.

As shown in [60], femtocells operating in open access mode together with proper pilot-auto configuration schemes can greatly reduce cross-tier interferences and lower probability of call drops. Another solution to cross-tier interference mitigation may be usage of CoMP [61]. CoMP is a method for coordinating data transmissions from several cells to one UE. Such technique not only reduces interference but also increases data rates in a location with poor reception from several cells simultaneously. Additionally, preference of access to the nearest femtocell compared to the femtocell with strongest RSS can improve performance from the UE point of view, especially in a dense network deployment [62].

Mobility. There are three sub problems mobility robust optimization, mobility load balancing, and Random Access Channel (RACH) optimization. Mobility Robust optimization plays important role in hand-over process. Manual setting of hand-over parameters is applied to standard cellular networks, but it is time-consuming and costly. Additionally, it cannot quickly reacts to changes after cell’s initial deployment. Therefore, BSs in SON architecture should be able to automatically adjust their mobility parameters and identify neighbours suitable and non-suitable for hand-over.

Mobility load balancing mechanism distribute traffic to less congested cells in the vicinity of heavy loaded cells which leads to improved overall system capacity. RACH is used for synchronization of uplink channel and to initial access to resources of cell. Performance of this channel should be regularly monitored, for example by random access delay. If an overload is detected then a preamble reallocation or reservation of additional physical resources should be triggered by an optimization function.

Coverage and capacity optimization. Coverage and capacity optimization has to be evaluated constantly to ensure desired level of QoS. There are several mechanisms as setting timing advance parameter, UE signalling and reporting, distribution of traffic load measurements, adapting power schemes, and antenna tilting for such purposes. Flexible optimization can be achieved through UE measurement reports and base station (NodeB or eNodeB) measurement, which is evaluated by optimization function.

Neighbourhood relation. Since a femtocell is a BS that contrary to a macrocell can suddenly be turned off and after a while, it can emerge in a different location, keeping list of neighbouring cells is not as straightforward. ANR is responsible for detection of neighbouring cells and collection of necessary information from them. One of the most important one is the Physical Cell Identity (PCI). The PCI serves as the primary identifier for discovering neighbouring cells. Neighbouring list can be managed in a cooperative way, where information are exchanged, e.g. via X2 interface, or non-cooperative way, there each BS is independent to each other and fully responsible for its own neighbour list. Standard methods for discovery of new neighbours, as radio-scanning, detection based on reports from mobile terminal, are valid but problem of hidden node may arise and have to be solved. Another issue with managing neighbour list in femtocell networks is how to keep it updated, especially in dense networks.[63]

Identification of femtocells - PCI Allocation. The PCI is the primary identifier in LTE networks, which UE reads. It is broadcasted on synchronization channels, therefore obtaining PCI identity is fast comparing to reading other identities transmitted on broadcast channel. There are 504 PCIs in LTE, which is much less than would be needed to assign unique PCI to each cell. Therefore, allocation of PCI has to be done under certain rules mentioned more thoroughly in later chapters. PCI primary serves to assist handover procedure. The secondary usage may consist in prompt identification of CSG cells in case a specific subset of PCI will be reserved for such CSG cells.

1.6.3 Network and Hardware related issues

A femtocell as CPE should be at lowest figure. Therefore, hardware is chosen mainly with regard to costs. It should provide only desired level of functionalities. There is no need to support redundancy and backing up whole mechanism, as device is cheap and not aimed to critical communication or be operating under heavy loading for a long time. However, femtocells are more exposed to security vulnerabilities and have to be precisely synchronized with a macrocellular network.

Security. Femtocells are exposed to security threats due to routing their traffic via internet. The main threats are Denial of Service (DoS) attacks, unauthorised access and/or service theft, Subscriber ID theft and interception [64]. Therefore, proper security precaution has to be enforced. The essential is using of secure communication method protocols with ciphering and strong authentication method. For this purpose, femtocells use Internet Protocol Security (IPSec) together with Internet Key Exchange version 2 (IKEv2), which among others supports Extensible Authentication Protocol (EAP) [65].

Synchronization. There are another challenges need to solve as a stability of reference clock due to network synchronization. Expensive stabilized oscillators are not solution, because a FAP should be cheap. The following three variants can solve the problem: usage of a network synchronization based on IEEE-1588 protocol, reference from Global Positioning System (GPS) signal or macrocellular reference signal, but each variant has some drawbacks.

1.6.4 Benefits and Services

One of the main advantages of FAPs in comparison to “standard” macrocellular BSs is their ability to do offloading, as they use fixed line to connect to a CN. Whereas femtocells decrease traffic from macrocell network, at the same time, they contribute to bigger volume of data going to a CN. The reason is that boosted quality of radio signal inside a building permits higher data-rates. Therefore, mobile core of a Mobile Network Operator (MNO) has to be able to deal with such elevation. However, adaptation of a CN to higher loading can be avoided, as main percentage of this traffic goes out of mobile network, and can be routed off core [66]. A femtocell gateway or a femtocell itself is capable to reroute traffic directing out of mobile network due to technique referred as Selected IP Traffic Offload (SIPTO). Hereby, femtocells are able to offload both macrocellular network and core network at once.

Presence of a femtocell in a Local Area Network (LAN) provides opportunity to access local resources (e.g. network printers, Network Attached Storages) from a UE. The Local IP Access (LIPA) and Remote IP Access (RIPA) were specified in Rel. 9 to establish such functionality [67]. LIPA service enables to access LAN resources through a femtocell with the proviso that a mobile terminal is attached to it [68]. RIPA service conveys connection to a LAN in case a UE is camped on a macrocell and the macrocell is able to connect to subscriber’s femtocell. Another contribution of femtocellular technology is that it helps mobile carriers to reduce their capital expenditure (CAPEX) because they can decrease amount of macro BSs need to build to ensure high-speed data rate services in a location. At the same time, femtocells are cheap alternative for grossing up a capacity. From the user point of view, a femtocell improves mobile signal thus allowing higher data-rates in indoor locations. Side effect of such improvement is enhancement of battery life of a UE [69].

Except technological and economic aspects, femtocells enables new range of so called location-based services (LBS) which are opportunity for mobile operators to generate additional revenues [70]. Since femtocells cover limited area, localization of users can be done much more precisely than in case of macrocells. The knowledge of exact position can be used e.g. to Smart delivery promoted by NEC [71]. Smart delivery service offers delivery of a parcel to a customer only at time when he/she is really being at home. The service is based on detection of a UE in a customer's FAP. Both courier companies and customer may profit from the service, because it reduces additional costs caused by repeating delivery and enables obtaining shipment sooner.

Other type of add-on services can be added via universal Application Programming Interface (API), e.g. Nokia present support of API for advanced application integration as advanced feature on WCDMA/LTE femtocells, which are supposed to operate in more than 12 countries [72]. In case of massive deployment, such feature can be opportunity for extra revenues not only for operators. The SCF presents some of most useful applications, which can be triggered automatically as user, enter or leave space covered by a femtocell. They are SMS delivery when children get home, fast podcast downloads, and automatic enabling/disabling media sharing [73]. Moreover, femtocells can help solve problem of localization of callers to emergency lines. A survey conducted between personnel of emergency call centres showed that people contact them mainly from indoors and in almost 90 %, callers are unable to provide their exact location to an operator [74]. Thus, precise detection of their location, in the extreme case, can save lives.

1.6.5 Architecture and deployment of femtocells

This subsection describes essentials of femtocells in term of their architecture and deployment, as both are very distinctive from macrocells. Specific features, which are fundamental to understanding femtocell concept much deeper, are pinpointed here. The general overview to the architecture of femtocells is illustrated on the following picture.

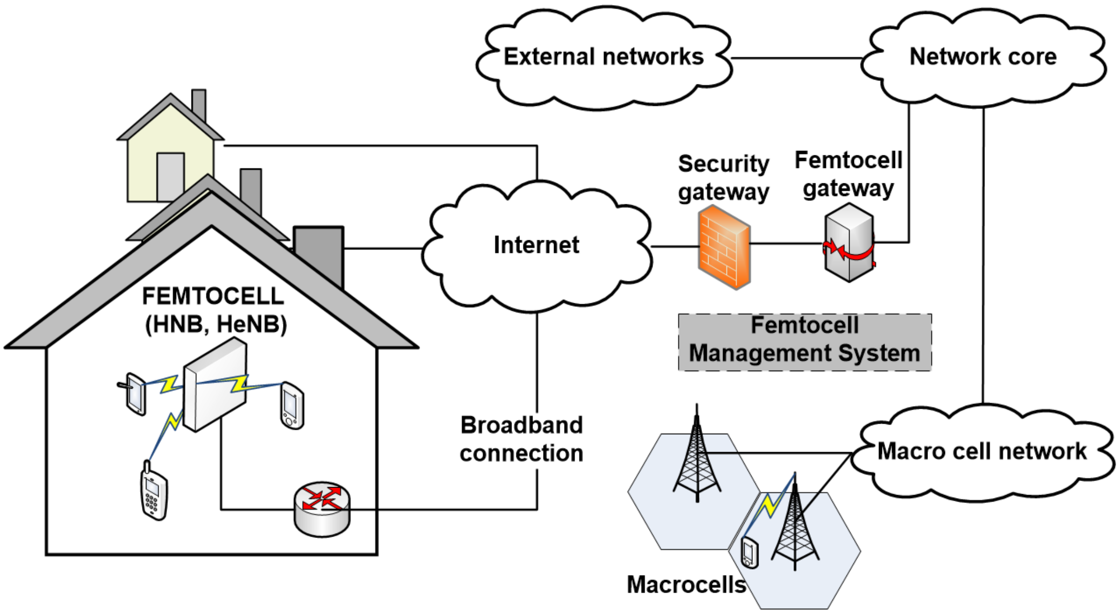

Figure 1.7 Basic femtocell topology.

On the picture above, you can see that a femtocell traffic is routed via broadband connection to the CN passing through the Security Gateway (Se-GW). The Se-GW protects against network threats and may be dedicated or incorporated into a FAP itself. The Femtocell gateway or HeNB/HNB-GW concentrates connection from many FAPs and ensures their authentication. The Femtocell management system, in LTE designated H(e)NB Management System (HMS), provides femtocell discovery services, sends corresponding settings to a FAP, and verification of location according popular Customer Premises Equipment Wide Area Network Management Protocol (CWMP) specified in TR-069 [75].

In term of interconnection with CN, division of femtocells' deployment is following:

- One connection to the HeNB-GW through S1 interface
- Two separate connections, one to the MME via the S1-MME interface and second to the Serving Gateway (S-GW) via the S1-U interface
- Two connections, one to the S-GW via the S1-U interface and second to the HeNB-GW via the S1 interface

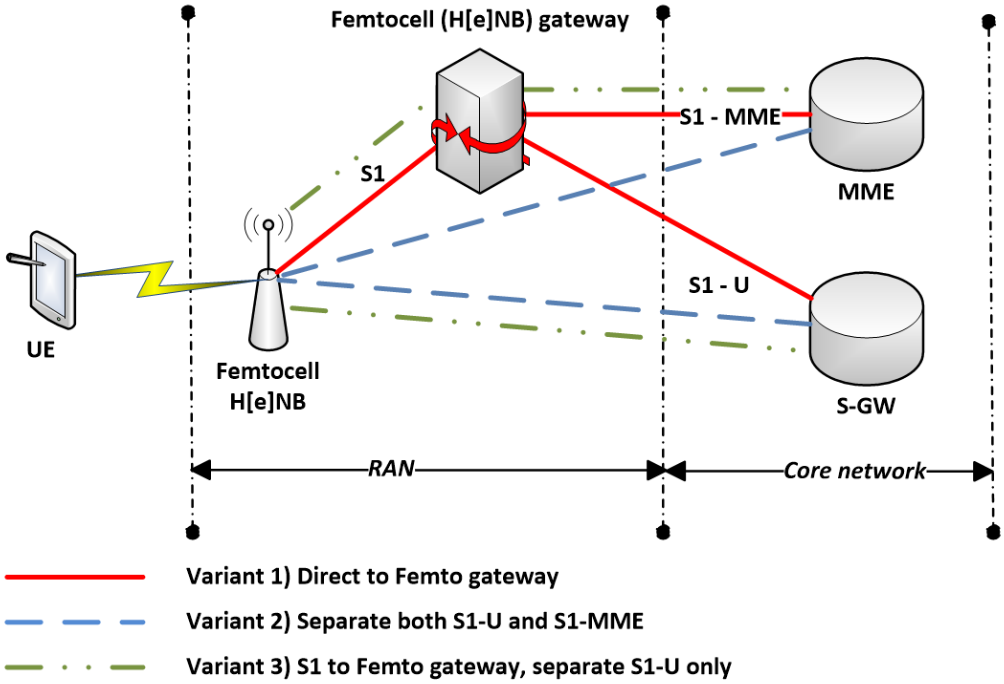

Figure 1.8 Ways of interconnection of HeNB with CN.

The variant with direct connection of the HeNB to the HeNB-GW is universal solution and both control pane and user pane information are concentrated at the HeNB-GW. The second solution is based on direct connection of signalling via the S1-MME interface to the MME, and a user traffic via the S1-U to the S-GW. It can increase overall system performance, whereas in the HeNB, it can cause performance degradation, because the HeNB has implement gateway functions itself. The third option routes control pane to the HeNB-GW and user pane connects directly to the S-GW, which increases throughput and allows concentrate signalling at the gateway.

1.6.6 Problem of identification in femtocells network

In homogenous mobile networks (those without femtocells / small cells), a network designer manually assigns a cell identity to each cell during planning period. Many planning tools provide required functionality to manage it. However, this approach cannot be employed in femtocell networks because:

- FAPs are dynamically emerging and disappearing according to user choice in unanticipated locations.
- Number of deployed femtocell BSs within certain area is much larger unlike macrocells whose count was optimized to satisfy area coverage with required capacity.

It is estimated that several hundred even several thousand femtocells could be active in an area around one km^2 in densely populated locations. Such density is real especially for ultra-dense networks coming with 5G. Since every femtocell in evolving mobile network such as 4G-LTE must have Physical Cell Identity (PCI) and range of this identity is limited, there has to be employed new techniques, which deal with these challenges. There are only 504 PCIs in LTE networks. Thus, range of identities available for an assignment is several times smaller than would be need, so it is necessary to introduce PCI re-use pattern. Proper configuration of Physical Cell Identity (PCI) is crucial to become a FAP operational. The problem could be solved having full-mesh topology, e.g. via X2 interface, and having each femtocell with capability to precisely determine its location. However, both of this is not achievable, full mesh due to high number of required connections, and location determination inside buildings due to high cost of such solution.

There is need to know more characteristics of a typical femtocell environment as probability of intersection, probability of collision, rate of intersection, and count of neighbouring femtocells considering different topology models to properly design or select algorithm for allocation of PCI. In addition, knowledge of how these characteristics are influenced by femtocell specific parameters as coverage distance, network parameters as number of deployed cells, and range of identities available to assignment, together with finding relation between them, help to correctly choose proper PCI selection algorithm. I use two different topology models in my thesis, which coincide with main purposes for using of femtocells as:

- Enhance coverage in an area with a 3G/4G mobile signal.
- Enhance the quality of signal (to enable achievement maximal data-rates supported by a network).

The first is the Random model, which constitutes rural areas with scarce population density and the second, the Dense Urban model, simulates urban locations otherwise densely populated areas.

1.7 Aims of thesis

My thesis deals with identification femtocells in mobile networks. The main part of my work is focused to LTE/LTE-A networks as the latest evolution phase. Nevertheless, some of the findings can be used independently on the concrete radio access technology. Mainly, the future 5G networks with ultra-dense networks are considered as the second area, which could profit from results presented here, because the cell densification is one of the most important concept of 5G networks. I study issues related to PCI allocation, which is limited resource and has to be provided under certain rules, because it is directly related to emitted radio signal. In brief, I deal primarily with these points in my thesis:

- Analysis of PCI allocation issues
- Proposal of models to evaluation of collision and confusion issues
- Evaluation of models and appointment indicators appropriate to solution of collision confusion issues in dense networks
- Comparison of the Random model and the Dense Urban model
- Suggestion of the scheme for automated PCI assignment based on simulations

The main contribution of this work is aimed to support solving assignment of Physical Cell Identifies as specified in Use Cases defined by 3GPP in TR.36.902. Another outcome of the thesis should be to clarify collision and confusion problems in femtocell networks, their frequency, and conditions influencing them, under different areas represented by various topology models. Therefore, outputs could assists in design or selection of proper algorithm for automated Physical Cell Identity (PCI) assignment. Some scenarios prove that setting of sophisticated algorithms, which are time-consuming and computationally exhaustive, can be substituted by simpler solutions and therefore this work appoints conditions when simpler or complex approach is need. Furthermore, it may serve as groundwork for similar problems not only in mobile networks but also in all networks using small cells.

1.8 Structure of work

I make short introduction on evolution of mobile networks and explain context leading to emerge of small cells and femtocells. The details about femtocell technology are presented in the subsection 1.6. Basics of femtocells are covered and some brief introduction to femtocell history is mentioned. It explains why the femtocell concept is natural evolution of BSs in mobile networks and the role of this concept for future evolvement. After it, I refer to basic radio related challenges that arise with femtocells. Main areas where novel methods contrary to macrocell networks has to be employed are interference management, synchronization, handover procedure, mobility etc. There is also quick background on possible solutions. Next subchapter covers network and hardware related issues that has to be managed in femtocell networks. All of these are mentioned to comprehend to femtocells, which is essential to propose any solution not colliding with others specific features of femtocells. Next part discusses benefits of femtocells in mobile networks. It is followed by sub-section that describes architecture principles and outlines basic deployment choices of femtocells in LTE networks.

The semi-final sub-chapter 1.7 explains aims of my thesis and states several points, which are covered in this thesis. The last subsection of the first chapter is introduction into identification in femtocell networks, where main sources of issues are identified together with overview of models used in my thesis.

Chapter 2

The chapter 2 is aimed to explain the process of identification of femtocells and related issues much deeper. Especially, the details on specifications of PCI in LTE networks are covered. The identities, which are defined in LTE networks as E-UTRAN Cell Global Identity, E-UTRAN eNB identity, Closed Subscriber Group Identity etc. are referred in this chapter. The subsection 2.1 covers basics of SON architecture, which has to be applied to femtocells. SON principles are important to manage femtocells effectively. The role of the Physical Cell identity is explicated in the sub-chapter 2.2. Importance of PCI in a handover process and collision and confusion issue is also discussed here. The sub-sections 2.3 and 2.4 are devoted to basic approaches solving automated PCI assignment in femtocell networks. Related works conducted in the framework of 3GPP as well as related papers of other authors are covered in these parts.

Chapter 3

I describe applied approaches, and develop much more on used models in the chapter 3. Overall description of performed simulations together with all constraints is mentioned here. There is definition of parameters for particular scenarios, which are designed to study collision and confusion.

The subchapter 3.3 presents the Random model, which serve as a basis for deployment of femtocells. It is intended as emulation of sub-urban deployment. The second model, the Dense Urban model is outlined in the subsection 3.4. This model serves to simulate urban deployment in highly populated areas, and to compare topology change. The subchapter 3.5 covers definitions of probability of collision and confusion issue, and equations applied in the thesis. The last subsection 3.6 describe used algorithm to evaluation of models.

Chapter 4

Results of simulations evaluated on both Random model and Dense Urban model are presented in this chapter. I state outcomes of the models regarding to collision and confusion issue here. At first results for random model are presented, then for dense urban model, and comparison is done at last subsection. Probability of collision and confusion is evaluated by simulations of Monte Carlo algorithm and graph oriented metrics, and clustering is studied here.

Chapter 5

This chapter build upon previous evaluation and draft schemes of automated identification assignment in mobile networks. There are two schemes of automated PCI assignment, which bring alternative to identification solution mentioned in other works. The first uses centralized approach to automated PCI allocation and the second one include solution from distributed perspective. Outcome of this is to tackle collision and confusion issue with limited resources.

Chapter 7

Last chapter introduce summary of main contribution of my thesis. Next section concludes findings mentioned in previous chapters, put them to context of current state in mobile networks, and clarify usage in the term of future mobile networks. Moreover, proposal on future work is listed in the chapter.

2 Identification femtocells

Allocation of unique identities to BSs before femtocells was not difficult task. The main reason was due to coordinated planning of deployment, when each BS was installed to chosen location after evaluation of overall performance and calculation relevant parameters on the site. Since femtocells respectively small cells came into scene, unplanned deployment is inevitable and new principles has to be applied for them. This brings new issues especially to radio related identities. Therefore, I explain process of identification of femtocells much deeply and mention related works in the chapter. The problem can be viewed in broader sense, not only to femtocell case, because modern network tends to be completely decentralized and autonomous, with as few signalling as possible.

A femtocell needs several identities to operate in a network. In E-UTRAN, there are defined the following identities and indicators [76]:

- E-UTRAN Cell Global Identifier (ECGI) – consists of the Public Land Mobile Network Identity (PLMN) and the Cell Identity (CI), used to identify a cell globally in a network
- Global eNB ID – consists of the PLMN and the eNB Identity, used to identify an eNB globally
- E-UTRAN Radio Access Bearer Identifier (E-RAB ID) – the identity of virtual session between a UE and an S-GW.
- Closed Subscriber Group Identity (CSG ID) – used to identify a CSG within a PLMN
- HeNB name/ CSG Type – is not the network identity as the previous ones, their purpose is to inform user about cell type or HeNB itself.

These are high-level identifiers, where is no major problem with assignment due to sufficient space. E.g., CSG ID has predefined range to 27 bits, which means there are more than 134 million unique Ids available. Similarly, the CI (part of ECGI) has range 28 bit, so in a network with unique PLMN ID, there can be placed more than 268 million cells, which seems to be reasonable high to accommodate all future extensions toward ultra-dense networks. However, on the physical layer, there is issue with assignment of Physical Cell Identity, which is tied with physical properties of a radio signal. Set of possible PCIs is limited and has to be allocated according certain rules.

2.1 Femtocell setup in term of SON

In term of operational efficiency, setting up of BSs was timely demanding process, when manual interaction on a site was only technique used to deploy them. Therefore, from the beginning of mobile networks, there were efforts to automate configuration and setting tasks as much as possible. It not only reduces expenses tied with deployment but also it speeds up whole process and brings greater flexibility. Different techniques were used to automate all kind of tasks as planning, tuning, dimension, and optimization in the past. Evolution of these is illustrated on the Figure 2.1. The latest mobile networks make towards Self-Organizing Networks. In the SON, network entities are responsible for self-configuration, self-optimization, and self-healing.

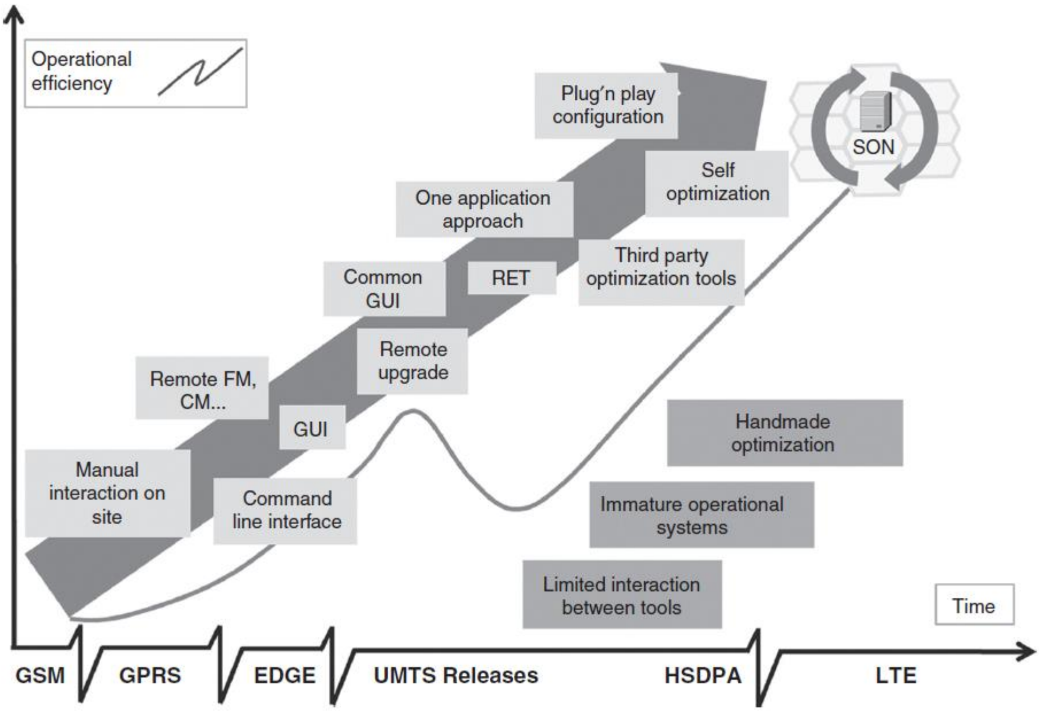

Figure 2.1 Operational efficiency of mobile networks towards SON. (Source [77])

SON principles are only viable alternative to effective operational management in femtocell networks. Manual configuration, even done remotely, requires many skilled staff to do relatively easy and repeated work. It not only makes the whole process more error-prone, but also increases fixed cost. Thus, self-configuration mechanism allows users to deploy a FAP operating in licensed bandwidth at home environment, which otherwise has to be done by a specialist. On the next picture, there is illustrated process of a femtocell deployment under

SON principles. The Figure 2.2 depicts all steps need to be done to transit from pre-operational to operational state [78].

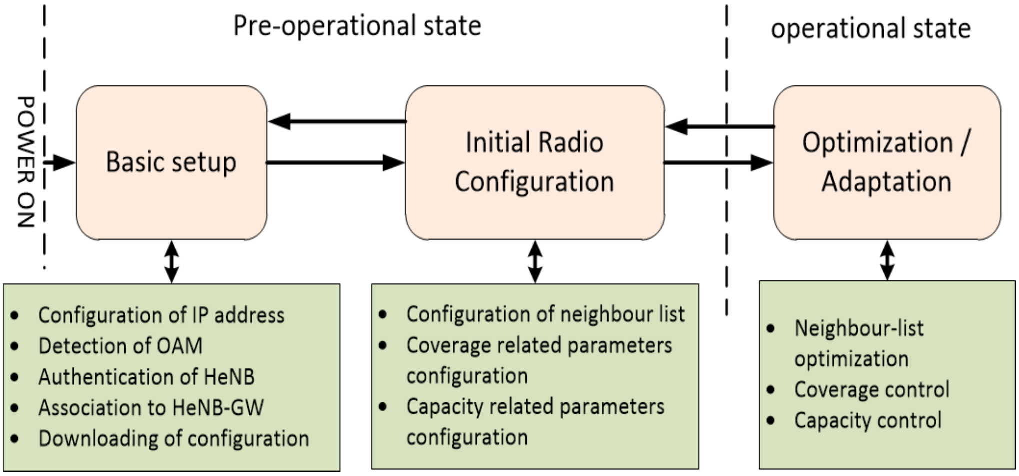

Figure 2.2 HeNB setup procedure in SON.

Prior to a femtocell become operational it has go through all above-mentioned steps. After a HeNB is powered on, it has to initiate the basic setup procedure, where choose an IP address, establish connection with a HeNB gateway or a Serving gateway (S-GW) (according the way of connection), authenticate and download configuration script provided by an operator. Next step is crucial and involve radio scanning and configuration of all radio related parameters to achieve required capacity and coverage. In addition, Neighbour-list through Automatic Neighbourhood Relation function is provided in this step. Upon successful radio configuration, a HeNB moves into operational state. In the state, it performs optimization and adaption regularly to ensure required QoS in dynamic environment. If a problem arises, e.g. high interference or a network connection loss, a HeNB may fall back into the previous configuration phase and try to reconfigure with a new setup. The effective algorithm to self-organizing resource allocation is proposed in [79]. There are evaluated several schemes to frequency allocation and power control for macro-femto dense networks. Nevertheless, the focus of this thesis is to initial setup procedure, where one of the main parameters need to setup is Physical Cell Identity (PCI).

A newly introduced FAP has to obtain or select a PCI from predefined and constrained range. The value of PCI could be determined with or without assistance of a network core. It depends on considered approach centralized or distributed [80]. The centralized approach engages an entity in a CN, which collects information across the network, and runs algorithms to select proper PCI. Generally, main logic is concentrated in a one big entity (or small set of entities), therefore a FAP can be made without complex logic for initial setup, and thus it can be manufactured with smaller costs. On another hand, a central entity must be more robust and all setting is more susceptible to failure due to limited number of managing nodes (a failure of centralized node can flow into outages of many FAPs). Moreover, overhead traffic, generated by devices sending data to support evaluation of settings, can greatly load a network and reduce throughput of user data. Advantages of such system are easy interconnection with additional data from CN, easier achievement of optimal solution due to knowledge information from all FAPs in a network, and easy orchestration, since eventual change in algorithms or redefining parameters has to be adjusted in a limited number of nodes.

The distributed mechanism passes operative algorithms to each FAP, so every cell is responsible for collecting all necessary information about its neighbours (e.g. through Automatic Neighbour Relation function – ANR) and PCI selection according accessible findings. The distributed approach has the advantage to avoid dependency on a central entity, thus is more fault tolerant, because failure of single node does not threaten any other part of a network. Additionally as each node solve only locally bounded issue with configuration, it is not overwhelmed and has not to consider messages from any other nodes, algorithms need not to be so robust and computational power can be several times lower compared to an entity in the centralized approach. The disadvantages are obvious, achievement of optimal solution may be limited, because each entity can cause interference to settings of other BSs, additional implementation of algorithms add to the costs of FAPs, and eventual orchestration of settings may be more complex task. Nevertheless, the distributed manner is considered as more perspective for future networks and full-autonomy of a node in a network is largely demanded.

The process of PCI automated configuration is also affected by FAP access mode (open, closed or hybrid) [81]. Closed access mode creates cross-tier interference because UEs not authorised near a closed mode femtocell cannot use it. These UEs have to be connected to a macrocell, which can cause that radio scanning from surrounding cells may be unreliable together with neighbour-list. Additionally, if closed access mode is applied, a certain set of PCI may be assigned to them. It splits size of PCI set into two groups and makes PCI allocation more challenging. On the contrary, open access mode mitigates cross-tier interference because a UE in the vicinity can be handed over from a macrocell to a femtocell. Open access mode is in term of self-configuration more convenient, as do not create constrains on PCI set and allows every UE to camp on every cell. Hereafter, an open access mode is assumed.

2.2 Physical Cell Identities

Physical Cell Identities are linked to pseudo-random reference signals and orthogonal sequences at physical layer enabling multi-cell environment in LTE networks. The PCI identities take values from 0 to 503 in LTE networks. PCI are similar to scrambling codes used in 3G/UMTS networks. In UMTS, there were 512 different scrambling sequences. Set of possible PCI is consisting of 168 reference signals (otherwise subgroups) with three unique orthogonal codes in each subgroup [82]. Concrete value of a PCI can be calculated according to next formula:

$$N_{\boldsymbol{ID}}^{CELL} = 3N_{ID}^{(1)} + N_{ID}^{(2)} \tag{1}$$

where $N_{\boldsymbol{ID}}^{CELL}$ is the final value of PCI, $N_{ID}^{(1)}$ is the value of reference signal in range from 0 to 167, and $N_{ID}^{(2)}$ is the number of chosen orthogonal sequence in range zero to three. In general, it is not need to restrain only to LTE networks and its 504 PCIs because outputs can be transferred into other networks with limited identities to allocation. However, in case of application to different networks, it is need to adapt to concrete logic of an identity allocation, which may differ there.

The PCI serves as the primary cell identity on the physical layer. It enables UEs to determine source of mobile signal. In handover procedure, it serves as primary identity, which a UE reports as handover candidate, because a UE can read it fast, unlike the ECGI. Acquisition of the PCI should be done in 5 ms interval contrary to 150 ms for ECGI. The reason is that reading of PCI can be done without full decoding of broadcasted channel. The 3GPP defines maximum delay for, for both intra-frequency and inter-frequency handover procedure as following [83]:

$$T_{\boldsymbol{INTERRUPT}} = T_{SEARCH} + T_{IU} + T_{RRC} + \ 20\,ms \tag{2}$$

where T_{SEARCH} is time to search unknown cells. The only case for handover to an unknown cell is when it is not initiated by UE measurement reports. T_{SEARCH} for known cells is zero.

T_{IU} is interval to acquisition of the first random access occasion and the value of it is up to 30 ms. T_{RRC} is time to process Radio Resource Configuration (RRC) reconfiguration request, *RRC connection re-configuration (intra-LTE mobility)*, and maximum defined time is set to 15 ms. The 20 ms serves as additional safety margin. Thus, interval of interruption should be under 65 ms at most. The user survey shows that people can detect pause in speech more than

100 – 120 ms long, which cause audible degradation of voice calls [84]. All together means the PCI is one of the most important radio related configuration parameters and task of allocation should be treated with highest priority.

If anyone wants to deal with PCI assignment, he needs to know definition of properly selected PCI. According to 3GPP, properly assigned PCI is that one which does not cause confusion or collision [85]. Collision is situation where two immediate neighbouring FAPs are allocated by the same PCI. It results to mutual interferences and due to them, there may be service outage for UEs located in the area, where the device receives signal from both cells simultaneously. Situation where two cells are in collision is depicted on the Figure 2.3.

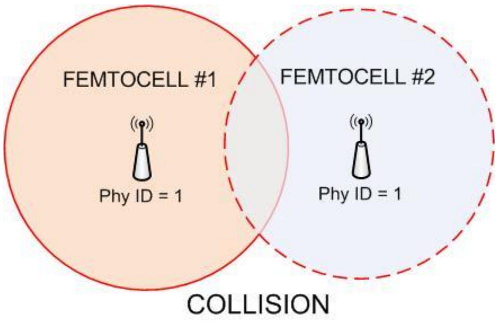

Figure 2.3 Femtocells in collision.

There are two immediate neighbouring cells have assigned the same PCI equal to one, which causes collision. A FAP or another network entity has to be equipped with mechanism to detect such situation and trigger immediate action to remedy this.

Another improper configuration scenario is confusion. Confusion happens when a FAP has two or more one-hop neighbours with the same PCI. At the simplest, there is one FAP between of femtocells with the same PCI. This situation may lead in wrong handover from the middle femtocell. Hand over could be initiated with incorrect FAP and thus, ongoing services would be dropped. The two different neighbours are detected according to the same PCI like the one cell. Cells in confusion are depicted on the Figure 2.4.

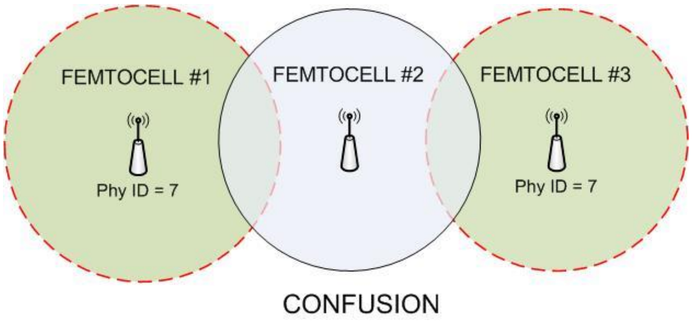

Figure 2.4 Femtocells in confusion.

Femtocell #2 is in confusion with #1 and #3. Handover from the middle FAP to both depicted neighbours can be unreliable and depends on propagation conditions. Detection of confusion is harder than a collision as femtocell #2 has not to detect all neighbours through ANR.

There are also other constraints for assignment of PCI as re-use distance, forbidden PCIs and modulo rule. Re-use distance should be maximised as much as possible to help mitigate interference. Forbidden PCIs means that some part of PCI range should be reserved for special purposes and modulo rule says that any neighbouring femtocell should not have PCI with the same modulo 3, 6, or 30 values [86]. This work is aimed to study different methods of PCI allocation and considers all neighbouring cells can be revealed by FAP itself, through UE measurement reports, scanning of radio environment, ANR function, or with assistance of a central entity.

2.3 Standardization outlines

Previous section outlines significance of Physical Cell Identity, mainly for femtocells, which have to be deployed autonomously. I mention possible approaches for solving automated PCI assignment in the subchapter. Formal requirements were identified by 3GPP and many research papers try to propose solution to automated PCI configuration. In the framework of 3GPP standardization body have been presented study by Nokia and Siemens, which drafts five different solutions to automated configuration of Physical Cell Identity. This proposal is not primarily aimed to concept of femtocells, but it may serve as groundwork from which femtocell automated assignment methods can be studied [87].

1) Randomized Physical Cell ID selection
2) Physical Cell ID selection after radio environment scanning
3) Physical Cell ID selection after the use of a temporary identifier
4) Physical Cell ID assignment by means of a central function and geo location
5) Physical Cell ID assignment by means of rollout planning

Abovementioned method can be categorized based on applied approach. Thus, methods one to three fall in category of distributed approaches and the rest can be classified as centralized approaches. The application of randomized PCI allocation is the simplest form, viewed as solution for deployment of isolated cells. Selection of proper PCI after radio environment scanning is heavily dependent to position of antenna of a BS and so unreliable. It is supposed that the BS should detect all neighbours. After the detection, the proper PCI should be selected and the BS becomes operational. Third method relies on temporal PCI, which enables to serve UEs instantly. Thus, the BS can learn from measurement reports about all neighbours. After certain period, when gather sufficient amount of data or after a timer run out, the BS select the proper PCI. The set of operational and temporal PCIs can be mutually exclusive. Fourth and fifth methods are similar in that they both depend on a central entity. In case of fourth method, central entity assigns PCI after deployment based on precise geolocation, contrary to fifth method, which propose to plan PCI before deployment.

Presented proposals have certain limitations in application to femtocells. The method 4 and 5 cannot be applied for them because rollout planning would limit a user to deploy a femtocell only in a location, which he reports in advance to a network carrier, and it needs to employ trained technician, who will responsible for setting parameters of every femtocell handed over to consumer. Assignment based on geo location data can be also excluded because femtocells are designed to be used inside of buildings where obtaining of geolocation from GPS is mostly impossible. Another means of geo location could be used but they do not provide necessary accuracy. Another disadvantage of centralized methods is heavy load toward the central entity managing configurations in femtocell networks.

Method 2 and 3 assume that all neighbours could be obtained by radio scanning and through measurement reports from UEs for collision-free assignment. The confusion-free PCI can be assigned after obtaining information about neighbours of neighbours, e.g. through X2 connection. Theoretically, these two methods should guarantee collision and confusion-free assignment, but, as stated in study, they do not, because UE measurement reports and radio scanning does not need discover all available neighbours. The first method is the simple assignment that cannot guarantee neither collision-free nor confusion-free assignment itself. Abovementioned paper only drafts methods for automated assignment but does not consider different scenarios and conditions when particular methods should be sufficient or insufficient.

2.4 Related works on PCI identity assignment

The papers dealing with assignment of the PCI identity can be divided into three categories, LTE-Standard Approach, Graph Colouring Approach, and Nokia-Siemens approach (referred in the previous section). However, many of them do not use scenarios, which can be appropriate to dense deployment of femtocells [88]. As LTE Standard Approach defines process loosely (based on known position and inter-cell communication via X2 interface), with two of four steps being optional, the other types of solutions, more sophisticated ones, are mentioned in the sub-section.

A solution based on identity assignment using graph colouring theorem, where each cell is treated as the vertex and neighbour relation is the edge, is described in [89]. Additionally, there are proposed optimization steps to affect various needs of mobile operators. Optimization is achieved by definition of flexible safety margin, which restraint of PCI re-use up to the certain neighbourhood level. The network simulations showed that even for safety margins above 12 levels it is possible to find valid PCI distribution with less than 504 colours. This approach is not aimed to specific features of femtocells. Graph colouring algorithms are popular technique to tackle collision and confusion and neural networks can be used to implement them. Neural networks with hill climbing optimization can solve not only collision, but also confusion free assignment within several hundred iterations on average and minimum number of required PCIs, as show in [90]. However, simulations were evaluated neither for dense network deployment nor for femtocells networks in the paper. Some specific features of femtocells as randomness in position can make such solution much more complex. Another graph-based solution with using the Glow-worm Swarm Optimization (GSO) algorithm can be found in [91]. Authors in the paper presents the improved GSO algorithm to solve PCI allocation, but it aimed to eNBs only and use GPS coordinates to obtain Euclidian distance. Similarly, the paper in [92] describes graph colouring method using Floyd algorithm with counting of cellular hops to obtain valid PCI distribution for small number of eNB.

According to the paper [93], a new cell should select temporary PCI and then use Automatic Neighbourhood Relation function to discover neighbours with assistance of messages exchanged via X2 interface. However, this is only coarse concept heavily depends on ANR.

Simple extension of PCI range could be viewed as the solution but it would require intervention to network design, especially to the physical layer. Such big intervention may cause problem in term of interoperability particular networks and UEs. Therefore, the extension of PCI range is complex task, which should be avoided. An example of study that proposes extending the PCI range up to 1008 Ids is presented in [94]. If the PCI set would be extended only to 1008 identities, it would be only mitigation of referred issues not final solution.

It is also possible to extend set of PCIs without changing physical layer specifications as stated in [95]. There is the virtual ID (vID) constructed from the ECGI and predefined number of bits, which cause shift of the zero System Frame Number (SFN) in the Master Information Block (MIB) against the reference SFN broadcasted by a macro cell. A UE should detect vID by measuring time offset between these (SFN) and appoint vID from it. Support of vID can be managed by an operator. Proposed solution extends PCI up to 10 bits in areas with high concentration of HeNBs. This expansion provides 1024 fold enlargement of PCI space, which is reasonable amount, but such solution cannot be scaled further. Thus, even large set of identities cannot also be viewed as final solution. Another paper deals with PCI allocation for FAPs with closed access mode. Authors suggest that the PCI should be combination of two parts. One part appointed by an eNB itself to prevent collision and other part determined by a network entity to make the identifier unique and confusion-free within a macro-cell [96]. Certain limitations of this proposal rest in that the central network entity would have to maintain the association between these two parts for each CSG-cell.

None of the previous works explores how often the collision problem arises, leading parameters of environment, which primarily influence rate of the issues. Additionally, they do not propose models to simulate real scenarios in term of these problems, with perspective towards dense-networks.

2.4.1 Centralized approach

The paper [97] deals with graph based PCI assignment done by centralized manner. It proposes that the central entity should collect information from eNBs and then uses colouring algorithm that has less time complexity compared to the paper [98]. Whole process of PCI assignment is consisting of these steps:

- Data obtaining
- Creation of the abstract graph
- Identification of neighbours
- Updating of Database (DB) and Neighbour Relation Table

In the first step, the necessary information about exact geolocation, cell radius, and list PCI neighbours are obtained for each eNB. Authors consider usage of GPS to get the position, the coverage optimization function to find out radius of a cell, and neighbourhood relation to get list of direct and distant neighbours.

Evaluation of information is done by improved graph-colouring algorithm. Improved algorithm is based on information about PCIs of neighbouring cells. Initially, the algorithm in the CN obtains list of cells up to third level (consider first level cells as direct neighbours) and then select the second level cell with the highest order (i.e. cell with the most neighbours). If the direct neighbours of this cell have the PCI, which is not chosen by any cell in the second or first level then this PCI is considered as the optimal PCI. On the contrary, if this not applies, the whole process continues with the second highest second level cell and so on. If none of the PCIs is chosen as the candidate, valid PCI is obtained from the set of all available PCIs in the network, which is not presented in any cells on the second or first level. An abnormal condition will appear when the number of direct neighbours, which new cell has, does not equal size of PCI set of direct neighbours. In this case, duplicate PCI values are presented in the direct neighbour PCI set and the PCI reassignment must be performed.

The whole concept relies on exact geolocation, which for femtocells may be unfeasible. Adding to that, the simulations are performed only on two small clusters with only so called initial setup, not evolutionary growth. The resultant time complexity around 110 ms for 15 cells may be considered large relative to ultra-dense networks.

The other study suggests tackling geolocation problems by using information from fixed network [99]. Authors propose identification schema in xDSL (xDigital Subscriber Line) networks, where each of PCIs is tied with the port number of the Digital Subscriber Line Access Multiplexer (DSLAM) and the Digital Loop Carrier (DLC) identity. The exact address of subscribers can be obtained by this way and converted to location. An assignment of PCI should be uniform over all ports of DSLAM. It combines random assignment with evaluation logic in the core. Such approach can be viewed as temporal solution not perspective mainly for ultra-dense networks.

The paper “Physical Cell Identity self-organization for Home eNodeB deployment in LTE” describes proposal to automated PCI assignment for femtocells operating in hybrid and closed access modes [100]. Authors consider a layered structure, which means the PCI set is divided into multiple layers based on different cell types. There is the layer for femtocells with open access mode, closed access mode, hybrid access mode and one layer is reserved to macrocells.

Authors propose PCI Assignment Function (PCI-AF) which controls the multiple layers of the PCI sets. The PCI-AF is located in the central entity in the core network. The PCI-AF can obtain ECGI and NCL of each eNB and femtocell. The automated assignment of PCI is proposed in the following way: femtocell scans for neighbour cells at first, collects their PCI, ECGI, and then sends these to PCI-AF. Acquiring of the ECGI is planned in autonomous gaps or network-scheduled gaps. The ECGI is then attached in the measurement reports. However, such acquisition negatively affects battery life of UEs. It might even end in interruption of on-going services. This problem intensifies especially in areas with dense deployment of femtocells belonging to CSG. A femtocell belonging to CSG reports only cells relevant to its group. Due to, the 3GPP defines parameter “*csg-PhysCellIdRange*” which limits PCI range of CSG cells into certain subset, UEs without the CSG membership may avoid useless acquisition. Femtocells in hybrid mode report all cells (macro, femto – open/hybrid). After that, the central entity randomly selects PCI, which is collision- and confusion-free with aforementioned and send it to the femtocell.

In case of emergence of newly deployed cells, there is a network topology change. Therefore, it is necessary to recheck NCL to ensure collision- and confusion-free state. Detected cells in collision/confusion except the one with the largest NCL would be restarted. Restarted cells have to do previous steps except the last one – rechecking. Simulation model has area of $1km^2$ and femtocells have been dropped into grid with various dense probability. The distance between each grid point is 100 m. All femtocells have been members of one CSG group. Results shows that number of PCI is limited even with large dense deployment. For dense probability 0.9, it is necessary 11 unique PCIs to make valid assignment.

The outcome shows that for CSG cells main issue is collision prior to confusion. Drawback of this proposal consists in a need to restart all femtocells involved in confusion issue and dependency on the central entity, which would be heavily loaded with information from femtocells. The simulation model where femtocells are placed into grid with 100 m distance between themselves does not affect densely populated areas.

The paper [101] proposes the Delay Registration (DR) algorithm to reduce signalling traffic in femtocells networks but such technique cannot be employed for the configuration phase.

The algorithm for Automated Distributing of PCI (ADPCI) and its less computational complex variant, suboptimal ADPCI (SADPCI) producing similar results is proposed in [102]. The ADPCI is based on the Minimum Spanning Tree (MST) algorithm and it considers cross-correlation properties of synchronization signals from which the PCI is derived. There is the comparison with Randomly Distributing PCI scheme (RDPCI) and Hypergraph Colouring PCI assigning scheme (HCPCI) evaluated on the eNB network with 50 cells. Among the cells there were distributed 6 and 30 PCIs and results shows that the proposed algorithms are capable under described conditions provide best results comparing to RDPCI and HCPCI algorithms.

2.4.2 Distributed approach

The study “Distributed graph colouring for self-organization in LTE-networks” in [103] describes automated PCI assignment by distributed manner. Authors deal with distributed graph-colouring algorithm to solve automated PCI assignment and Primary Component Carrier selection. They appoint that most of algorithms focus on finding colourings according to the largest number of neighbours of any node plus one. Rapidly converging algorithms exist for these cases, but if the largest number of neighbours of any node is larger than number of colours, different algorithm should be employed, e.g. generic satisfaction algorithm may be used. They refer to Distributed Breakout (DBO), Asynchronous Backtracking (ABT), Asynchronous Weak-Commitment (AWC) search, Distributed Stochastic Algorithms (DSA). Additionally, they choose four simple local search algorithms (two variants of binary pricing, two variants of real pricing) for simulations.

Their simulations are conducted on a model, which uses Manhattan grid. The model supposes that all BSs have been collecting information from their coverage area for sufficient amount of time before the reconfiguration starts. UEs are distributed by one into each room and five per the corridor. This should provide sufficient information to eNBs. Network is growing from 86 to 96 cells. Process of automated PCI assignment according to authors should be the following. A BS firstly scans for synchronization channel of neighbours and randomly selects PCI except that one used by discovered neighbours. This does not ensure collision free assignment because newly emerged BS can recognize only neighbours with synchronization signals above certain threshold. After this, newly deployed BS starts serving UEs, collecting hand-over candidates, and performing ANR function to connect with the neighbours. It is assumed that the conflict of PCI can be identified through ANR between neighbours involved in collision. Each of mentioned algorithms is then performed to ensure collision-free and confusion-free state. The algorithms run until they converge or until 1000 iterations have been done.

Results of the study show that all algorithms, except the random-try real-pricing algorithm, converge within 1000 iterations with number of used PCIs equal to 15. The AWC is concluded as best algorithm when it comes to convergence but this algorithm needs an additional protocol to communicate with cells, which are not two-hop neighbours. Binary pricing converge with 12 PCIs and multiple-try real pricing algorithm converge with 15 PCIs. In the term of number of reboots, the multiple-try algorithms are better than random selection algorithms. They conclude that it is counterproductive to reserve a part of the space for newly switched on cells because then there is always at least one reboot per added cell. They recommend AWC for solutions which are extremely greedy for low number of PCI's and for solutions less exacting for PCIs savings is recommended multiple-try local search algorithm based on binary confusion pricing.

2.4.3 Circle intersection

The collision and confusion issue could be also viewed in term of circles intersection problem. The circle is idealized representation of femtocell’s coverage for study purposes; this simplification for instance is used in the study [104]. The study [105] presents geometrical background for intersection of three circles, mentioning that evaluation of intersection is dependent to mutual position of circles. Moreover, there are derived the closed-form of algebraic formulas to compute intersection of three circles in case that this three circles are intersecting in such way that circular triangle exists. The algorithmic solution for computing an overlapping area, the area where two neighbouring circles intersects, is complex task for more than three circles, but paper [106] shows systematic approach to appoint it by proposing trellis structure with auxiliary variables. Authors have considered predefined layout circles so that their mutual position has been known. Analytical solution for case where vast number of circles with multiple unanticipated adjacencies is randomly placed would be quite complex problem even with trellis structure for femtocell networks. The proposed algorithm can also be used as the metric for optimal BS placement. One of the results shows ratio of overlay of randomly placed circles in a bounded area. The output is illustrated on the Figure 2.5.

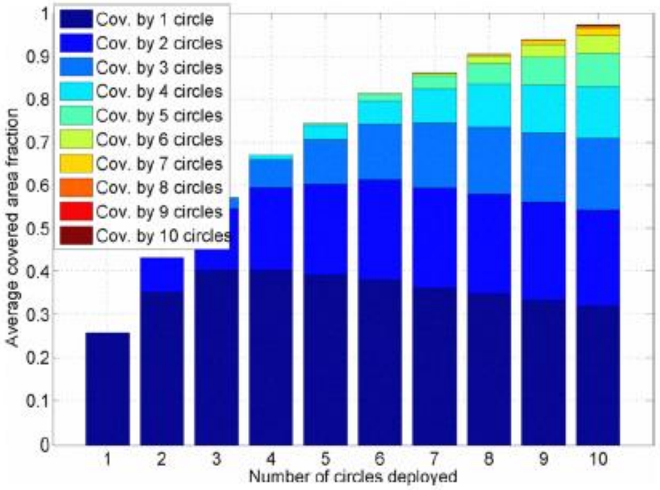

Figure 2.5 Covered area to number of overlapped circles. (Source [106])

Another work dealing with circle intersection problem can be found in [107]. The paper is focused on exploitation of circle intersection for location of mobile stations, but more than three intersection are not considered. The study [108] uses circle intersection to improve localization in mobile networks. Authors presents geometry approach based on simple calculations repeated several times to estimate a precise location of UE. Goal of this is easy implementation. Comparison of best range-free algorithm with algorithm based on computational geometry can be found in [109]. The outcomes are used to tackle localization problem in a sensor networks.

Solution of circle intersection enables calculation or at least estimation of total area occupied by femtocells. If a total area is known then probability of intersection, collision and confusion can be evaluated. Purpose of these probability characteristics is to serve as indices in designing and selection proper algorithm dealing with PCI assignment. The main challenge in solving circle intersection problem representing femtocells is the fact that femtocells can unpredictably and multiply overlap among themselves in great numbers. Circle intersection problem for obtaining probability characteristics could also solved by Monte Carlo method (as described in the latter section). This adaptation is performed because of random position of femtocells in mobile network and their large quantity.

3 Topology models and used approach

My thesis is aimed to analyse collision and confusion issue in the term of automated PCI configuration. Therefore, I create two topology models and conduct simulations under different conditions, which are described in the chapter. Main efforts are devoted to evaluation of probability characteristics, appointment of particular indicators easing PCI allocation for densely deployed femtocells in a macrocell area. All of these are in accordance with anticipated evolution of mobile networks towards ultra-dense networks.

General strategy to simulation is network evolutional growth. It means that a FAP is introduced among chosen number of pre-deployed FAPs. All of these FAPs are considered to be inside a single macrocell. The new FAP resembles cell that was recently switched on and the rest are regarded as properly configured cells in operational state.

Evolutionary growth is not only the case studied here as some scenarios are evaluated for all of deployed cells at once. This can be considered as initial setup phase of deployment, where no FAP is in operating state and several FAPs were deployed simultaneously trying to self-configure themselves. This brings other point of view on the problematics as there are multiple concurrent request to setup and neighbour relation is completely meaningless here as none relation exists yet.

The two different models are called Random model (RANDM) and Dense Urban model (DUM). Every model uses different layout to deploy FAPs within a macrocell. Each of simulations conducted here can be characterized by these points:

- Topology model (RANDM, DUM)
- FAP coverage distance (cell radius)
- Number of FAPs deployed inside macrocell

3.1 Adjacency

A femtocell topology can be represented as a graph $G(V, E)$, where FAPs corresponds to vertices (V) and links among them corresponds to edges (E). The presence or absence of an edge between any pair of vertices x and y, $(x, y) \epsilon V$ is appointed according to definition of adjacency, which is different for each model. FAPs are referred as direct neighbours, denoted as one-hop or first-level neighbours, when they conform to condition of adjacency. It can be illustrated by interconnection between corresponding vertices in graph. A set of one-hop neighbours, $N_{1H}(v)$, can be expressed as:

$$N_{1H}(v) = \{U: e_{uv} \in E\} \tag{3}$$

where e_{uv} is an edge between vertices u and v, and E is set of all possible edges defined according to neighbourhood relation function. Apart of the one-hop neighbours, I also assume neighbours of neighbours, called two-hop, or second-level neighbours. The two-hop neighbour is such FAP where neighbourhood relation exists between the suggested FAP and its one-hop neighbour and at the same time between one-hop neighbour FAP and its direct neighbour FAP. A set of two-hop neighbours of vertex w, $N_{2H}(w)$, can be expressed as:

$$N_{2H}(w) = \left\{V: e_{uw} \in E \bigwedge e_{uv} \in E \bigwedge e_{vw} \in \emptyset\right\} \tag{4}$$

where e_{uw}, e_{vw} are edges between vertices u and w, resp. v and w, and E is set of all possible edges defined according to neighbourhood relation function. The one-hop and two-hop neighbours notation is illustrated in the Figure 3.1. In the figure, the FAP_A has three one-hop neighbours (FAP_{AA}, FAP_{AB}, FAP_{AC}) and two two-hop neighbours (FAP_{AAA}, FAB_{AAB}).

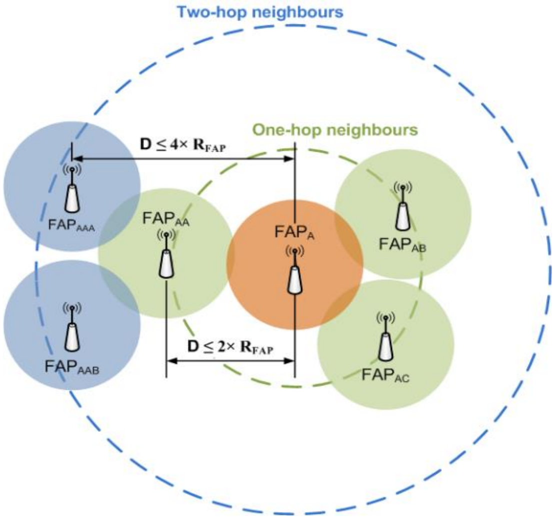

Figure 3.1 One-hop and two-hop neighbours.

On the picture above, there is overall explanation of neighbourhood levels, which can be extended to more levels with the same principle.

3.2 Clusters

Randomly deployed FAPs can be part of a cluster. It is accumulation of FAPs in a limited area, where interconnection between any pair of FAPs can be created through definite number of other FAPs. In term of graph theory, a cluster is formed by all vertices v such as that an edge e exists among any pair of vertices involved in the cluster and none path exists outside a given cluster in a graph G. A path is created by n-edges (n>1) defined according neighbourhood relation. A cluster C is specified as:

$$C = \{v_1, v_2, \dots v_n\} \in G : \forall \{v_i, v_j\}, i, j = 1, \dots n \ \exists \, P_{ij} = \{e_k\}, k \in N \tag{5}$$

where P represents path of length k between any of two vertices in a cluster.

A cluster is signification term in distributed solutions with cooperative mechanisms, because any exchange of information among FAPs is possible only inside of the cluster and information can be obtained by any FAP in the given cluster. I apply Breadth-first search algorithm [110] to find out clusters in the graph. Moreover, the algorithm is used to calculate distances between FAPs. I utilize the graph density (*GD)* to characterize clusters in term of number of interconnections among FAPs, which can be written as [111]:

$$GD = \frac{2|E|}{|V| * (|V| - 1)} \tag{6}$$

where $|E|$, respectively $|V|$, is the number of edges, respectively the number of vertices.

A cluster of FAPs can be described through different parameters, for example minimal distance between edges, maximal length of path, number of edges, etc. In the thesis, I use the maximal degree of vertex per cluster, size of cluster and number of clusters. The Maximal degree of vertex, δ, helps to estimate an upper limit of chromatic number, χ, of graph G [112], where the χ can be used to appoint maximal size of PCI set. Similarly, size of clusters helps to estimate complexity of neighbourhood relations per cluster.

3.3 Random Model

Random model (RANDM). The first and basic scheme considers FAPs randomly distributed inside a macrocell. Randomness in position of each FAP has a constraint, thus the position of each FAP is not truly random. The constraint for randomness prohibits the centre point of every pseudo-random FAP inside a macrocell to be closer than five meters to any other FAP. This limitation was adopted to emulate real world scenario more appropriate way because, except few exceptions, it can be anticipated that a femtocell will not be placed in the immediate vicinity of another femtocell.

The positions of FAPs are randomly generated with uniform distribution within a macrocell area and the following equations are used to conform this requirement.

$$d_C = R_M * \sqrt{U\ (0{,}1)} \tag{7}$$

$$\theta = U(0{,}2\pi) \tag{8}$$

where d_C is distance between the randomly placed FAP and the centre of macrocell BS with radius R_M, Θ is angle and U is uniform distribution function. Generating positions from equations (7) and (8) ensures uniform distribution of FAPs within a macrocell area, but the above-mentioned constraint is applied and thus after generation of each random position, there is applied another function to check whether the constraint is not broken.

The RANDM model also defines circumstances under which two femtocells are considered as neighbouring – definition of adjacency. There are two variants for determination of neighbourhood. The first variant considers two FAPs as neighbouring, when their mutual (Euclidian) distance is lower than a double of their radii, R_{FAP}.

$$\|X, Y\| \leq 2\ R_{FAP} \tag{9}$$

where X and Y denotes position of FAP_X respectively FAPy.

The second variant is also based on Euclidian distance but additionally introduce variable offset, which is added to radius of each cell. Each cell has redefined radius, which is consisting of value of radius itself and offset value, d_{OFF}, which is treated as safety margin.

$$\|X, Y\| \leq 2\ R_{FAP} + d_{OFF} \tag{10}$$

Different definition of neighbourhood relation makes the model more flexible and allows studying how the results vary by change of the relation. Moreover, such modularity eases incorporating of any other neighbourhood relation if this principles need to be applied to a concrete case.

Realization of the RANDM with custom scenario is depicted on the Figure 3.2. The picture illustrates random distribution of femtocells in the macrocell with radius of 564 m. There are some areas more congested with cells and some spots are free of cells as it can be anticipated in the real world.

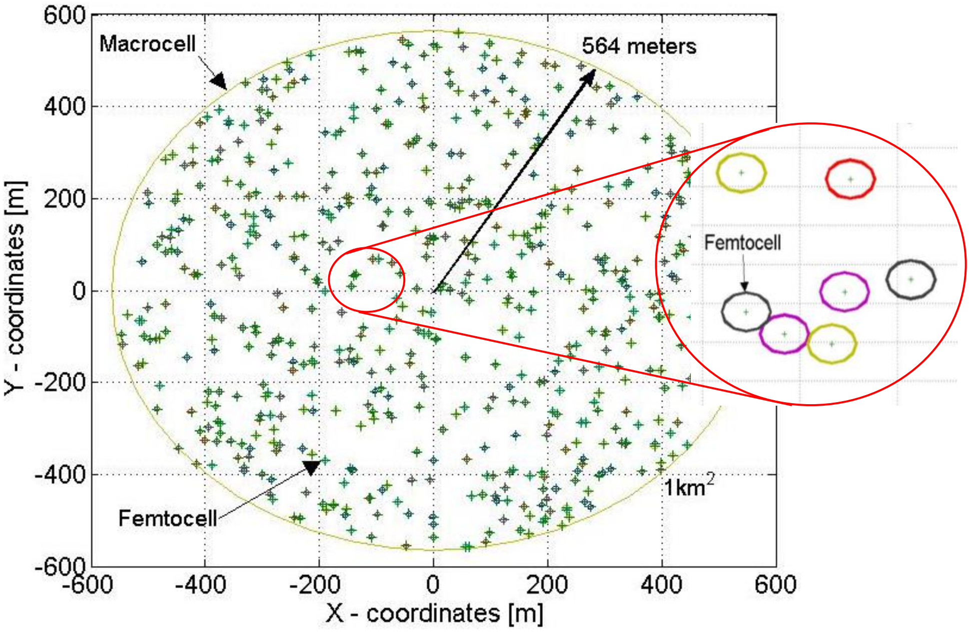

Figure 3.2 RANDM – Random model topology.

Another view on the random deployment can be made if the area is split into smaller sub-areas / sectors and sum of cells in these areas is depicted. A density of femtocells in a sector can be expressed by colours. Thus, the heat-map of the femtocell density in the macrocell can be made up. Example of heat-map with 1000 femtocells is illustrated on the next picture.

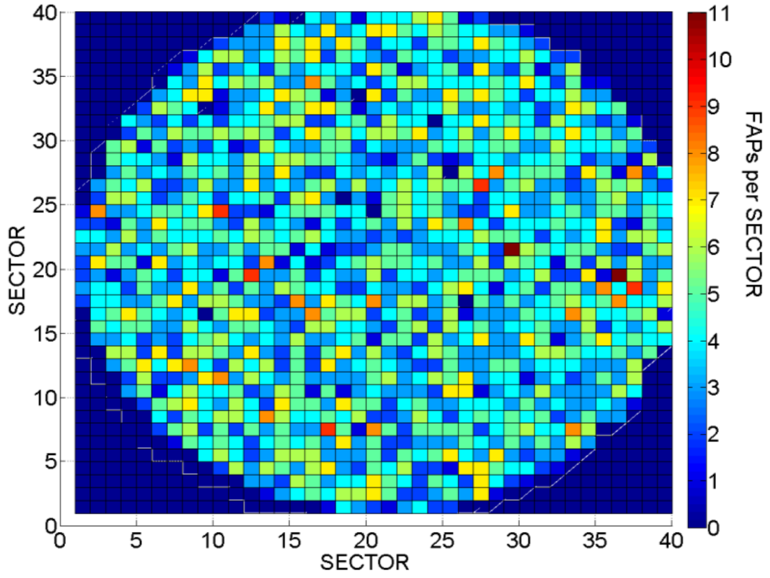

Figure 3.3 Heat-map of 1000 randomly deployed femtocells in a macrocell

The all macro cell area is divided into squares with dimension 50 x 50 m. Red colour represents the sector with highest density of femtocells. There is approximately more than nine femtocells in such sectors. From the distribution, it can be seen relatively small percentage of high-density sectors. Therefore, collision and confusion will not happen frequently in such scenario.

3.4 Dense Urban Model

The DUM, the second model, introduces layout of FAPs as can be considered in urban areas with residential quarters. It is based on model for small cells referred in [113]. The DUM consists of tenements, which make up square grid. Each tenement has overall 10 equally large flats with balcony area. Flats are organized into two rows, thus there are five flats in each row. The model assumes windows on outer wall of particular tenements. The area between particular tenements represents the street. Width of the street is the same both in horizontal and vertical direction. Dimensions of street lie in range from 5 to 40 meters. FAPs can be positioned only in the centre of each flat. The fact whether FAP is present or not inside flat depends on random function, which chose random number of positions from all available positions across all flats and tenements. The probability of presence of i-th femtocell in a free flat can be calculated like this.

$$p(i)_{FAP} = \frac{1}{N_{FLATS} - (i - 1)} \tag{11}$$

The adjacency between FAPs in the DUM is appointed by fixed definition of neighbourhood relation or by Euclidian distance, the same as in case of RANDM. The fixed definitions of neighbourhood relation are shown on the next picture, the Figure 3.4. The upper part shows neighbour relation variant referred to as R_A and the second variant, on the lower part of picture, referred to as R_B.

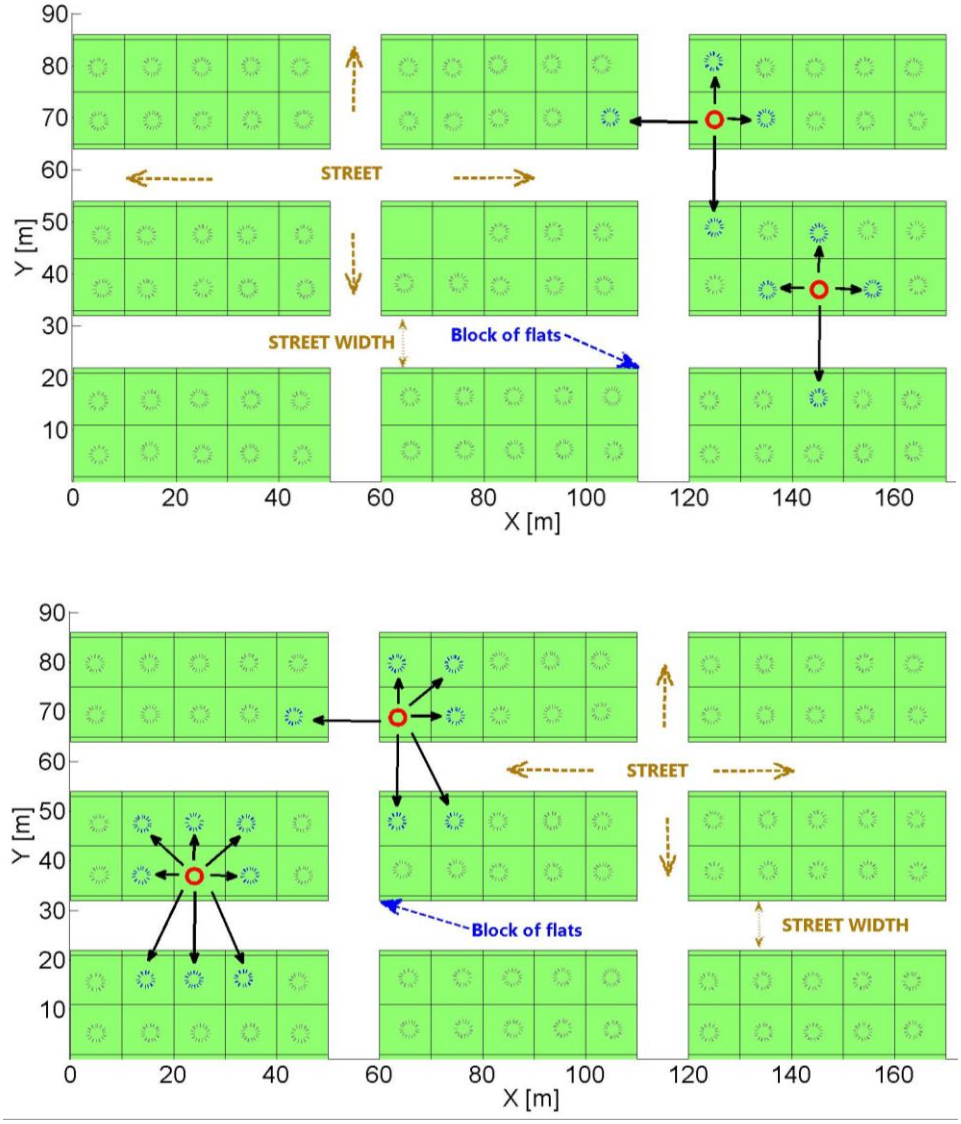

Figure 3.4 DUM – Definition of neighborhood relation variants..

The upper part of the picture is referred as R_A and lower part as R_B. Since, the dense urban model assumes windows on outer walls of particular tenement and there is better propagation of a signal through windows than through walls of a house, therefore neighbourhood relations were appointed as shown on the Figure 3.4. The variant R_A has maximum of four neighbours and the variant R_B maximum of eight neighbouring FAPs.

3.5 Probability of collision and confusion

DUM and RANDM use Monte Carlo method to estimate probability of intersection, collision, confusion, and derived characteristics. The algorithm computing probability is the same to both models except aforementioned differences. The Monte Carlo method substitutes computation of the area occupied by FAPs, especially for scenarios with evolutional growth. The analytical evaluation would have high degree of complexity because a FAP can have multiple unanticipated intersections with another FAPs, as there would be different intersection situation for every random deployment which requires extensive analysis. The area occupied by FAPs, labelled as A_{FAP}, obtained by Monte Carlo method then can be used in the equation of geometrical probability of intersection for newly generated cell in evolutional growth scenarios according to the following formula:

$$p_I = \frac{A_{FAP}}{2 * \int_{-R}^{R} \sqrt{R^2 - x^2} dx} \tag{12}$$

where A_{FAP} – area occupied by FAPs, R – macrocell radius, p_I – probability of intersection. Probability of intersection shows how often the newly deployed cell at the random position has adjacency to any of other pre-deployed FAPs. The form of adjacency can defined differently as mentioned in section describing models. In the event when two or more FAPs are neighbouring, it means that collision could happen, but not necessarily in all cases. It depends on set of identities available for allocation to FAPs. If we know the total amount of applicable identities then it is possible to appoint overall deterministic probability of collision. Initially we need to know a probability of collision for newly generated cell in case where count of neighbours is determined. This can be done by the following equation:

$$p_{DetCOL} = \frac{N_{NEIGH1}}{N_{IDs}} \tag{13}$$

where p_{DetCOL} is probability of collision in case that count of neighbours for a new cell is deterministic. N_{NEIGH1} and N_{IDs} are numbers of neighbours and available identities. If we do not know the exact number of neighbours, stochastic case, we can use the probability density for number of neighbours obtained from Monte Carlo algorithm and use it to estimate the probability of collision by this equation

$$p_{COL} = \sum_{K=1}^{\infty} p_{DetCOL} * p_k^{NEIGH1} \tag{14}$$

p_{COL} probability of collision, p_k^{NEIGH1} is value of the probability density for K neighbours. The formula represents the fact that every single event (a case where a newly emerged cell has exactly K one-hop neighbours with certain probability level) is mutually exclusive to each other thus the probability of collision is sum of all possible cases (i.e. the cases that a new femtocell will have from 0 to infinity neighbours).

In case that the newly introduced femtocell has more than one neighbouring cell, it can occurs the issue called confusion. The probability of confusion, p_{CONF}, is influenced by the number of neighbouring cells and by the number of available identities. The probability of confusion is sum of two different events: the new cell may be confused and the new cell can cause confusion to some cells around it. The first case, the probability that the newly inserted cell may be confused, denoted *MBC*, means that any pair of the one-hop neighbours has the same identity. It results that the new cell considers these neighbours as the one cell. The probability of this event mostly depends on the number of pairs that can be created from the one-hop neighbours.

$$p_{DetMBC} = 1 - \left(\frac{1}{N_{ID}}\right)^{C_2^{K1}} \tag{15}$$

where p_{DetMBC} is the probability that newly inserted cell may be confused by some of the one-hop cells at known number of the one-hop neighbours, N_{IDs} is a number of identifiers and $C^{K1}{}_2$ is a number of possible pairs from K neighbouring one-hop cells. If we do not know the exact number of the one-hop cells, the probability that the new cell may be confused is calculated from the probability function for the number of the one-hop cells.

$$p_{MBC} = \sum_{k=1}^{\infty} p_{DetMBC} * p_k^{NEIGH1} \tag{16}$$

where p_{MBC} is probability that newly inserted cell may be confused by any of the one-hop cells.

The second case, the probability that the newly inserted cell can cause the confusion, denoted *CCC*, to any of its neighbours, means that the newly inserted cell has the same identity as at least one of the two-hop neighbours. The probability of such event depends mainly on the number of the two-hop neighbours.

$$p_{DetCCC=}\frac{N_{NEIGH2}}{N_{IDs}} \tag{17}$$

where P_{DetCCC} is the probability that the newly inserted cell can cause confusion to any of the one-hop cells at known number of the two-hop neighbours (N_{NEIGH_2}), N_{IDs} is the number of identifiers. The probability function of the number of two-hop neighbours is also used to appoint the probability that the newly inserted cell can cause confusion for situations with unknown number of the two-hop cells according to:

$$p_{CCC=}\sum_{k=1}^{\infty} p_{DetCCC} * p_k^{NEIGH2} \tag{18}$$

where p_{CCC} is the probability that a newly inserted can cause confusion to any of its one-hop neighbours at condition of unknown number of the two-hop cells and p_k^{NEIGH2} is the probability density for the two-hop neighbours and. The overall probability of confusion, p_{CONF}, is sum of can cause confusion and may be confused events.

$$p_{CONF} = p_{CCC} + p_{MBC} \tag{19}$$

p_{CONF} is the probability that newly inserted cell is in a confusion situation.

3.6 Description of used algorithm

The evolution growth scenarios are designed by the following way to obtain probability characteristics for collision and confusion issue. At the first step, the chosen number of FAPs is distributed inside the macrocell. Their location is random according to used model. For RANDM, position of each FAP is random with restriction that prohibits any pair of FAPs to have distance between them closer than 5 meters. For DUM, random position is the centre of randomly chosen flat. It is considered that every FAP has the same coverage area. Next there is generated 10 000 randomly positioned points (in compliance with the corresponding model) representing newly emerged cell. These points make up particular iterations, which simulate repeated insertion of the new cell to cope with its randomness. In each of 10 000 iterations, there is evaluated whether or not this point has adjacency with any other FAP. If intersection exists, then it is recorded how many adjacencies have arisen. The resulting values are applied to before-mentioned equations. RANDM and DUM are evaluated with different input parameters to find out dependencies. The table presenting used inputs is listed below.

Table 3-1 Input parameters range

Parameter name	**Range**
Macrocell area	1 km2
FAP's coverage dist.	5 – 20 m
Number of pre-installed FAPs	50 – 10000
Monte Carlo N iterations	10 000
DUM street width	5 – 40 m
Number of Physical Ids (LTE)	504

3.7 Discussion

Collision and confusion issue is major problem at physical layer, which can lead to service outages, and improper handover, which is unacceptable for evolving mobile networks with high date-rates. Therefore, I propose two models, Random and Dense urban model, which deploy femtocells by the defined way in a macrocell area. The models consist of function responsible for femtocell placement and neighbourhood relation function, which appoints the adjacency of femtocells. This neighbourhood function can be arbitrarily switched if needed to affect different conditions or aspects. The RANDM employs two definitions of adjacency and the DUM has defined three different ones. I define boundary for model parameters under which the evaluations were conducted. Macrocell has defined area of 1 km^2 and 50 to 10 000 FAP with radius from 5 to 40 meters is placed according the model inside the macrocell. I also define probability characteristics as the probability of collision, confusion, and intersection here. The graph theory terms used for simulations is also referred. Simulations are conducted with Monte Carlo method, which enable deal with randomness of femtocell position. There are two basic scenarios. One is evolutionary growth and the second is initial setup affecting different configuration phases of a mobile network.

4 Evaluation of models

This section of my thesis presents results obtained according to previously mentioned approaches and equations. The findings obtained from evaluation of the RANDM are shown first. Most of hereto-presented figures have the same structure. The x-axis marks number of pre-deployed femtocells and the y-axis is reserved to evaluated quantity, e.g. the probability of collision. The radius of FAP is put as the parameter in the chart. All simulations were performed in MATLAB software.

4.1 Random Model

The newly deployed FAP at the random position within the macrocell may have a different number of neighbours. As mentioned earlier, the different way of femtocell deployment contrary to standard BS makes impossible to determine exact number of neighbours before its activation at the exact location. However, the probability characteristics of random deployment can be estimated by conducting simulations. There is also need to know count of identities, which can be assigned to enumerate probability of collision/confusion. As 4G-LTE networks are considered here, the value of 504 Physical Cell Identities is taken into account. Principles mentioned in my thesis are not limited only to such number of identities and can be replaced by an arbitrary number of identities or some other limited resources in a network.

Probability of collision in Random model. The Figure 4.1 shows the probability of collision, p_{COL}, for the newly inserted femtocell among N other FAPs. The neighbourhood relation is set when the distance between cells is lesser than double of their radius. The figure displays linear dependency to number of pre-deployed FAPs. The probability of collision is increasing with growing number of FAPs and with scaling up of femtocell radius. In case of 5000 pre-deployed FAPs with 20 m radius, the probability of collision is around 4.7 %. It is so negligible value that in term of collision it is possible an assignment of identities by random algorithm triggered locally. Collision detection and self-repairing mechanism has to be added to detect and remedy the situation. Self-repairing algorithm can be simple re-triggering of random algorithm for example.

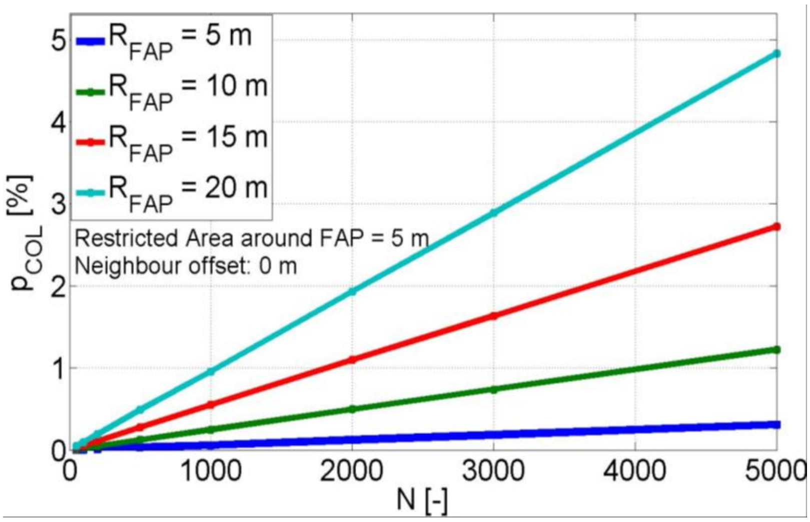

Figure 4.1 RANDM – Probability of collision to number of FAPs.

The next figure differs from the previous one by the way of determination the neighbourhood relation. There are cells considered as neighbouring when the distance between them is less than double of their radius to which is added offset of 20 m respectively 100 m, as shown in the left part respectively right part of the picture. The p_{COL} is increased approximately twice for 20 m offset. The introduced offset can be viewed as safety margin, when the newly inserted cell can interfere not only with the cells in the immediate vicinity, but due to specific propagation condition, it could interfere with additional cells that are more distant as well.

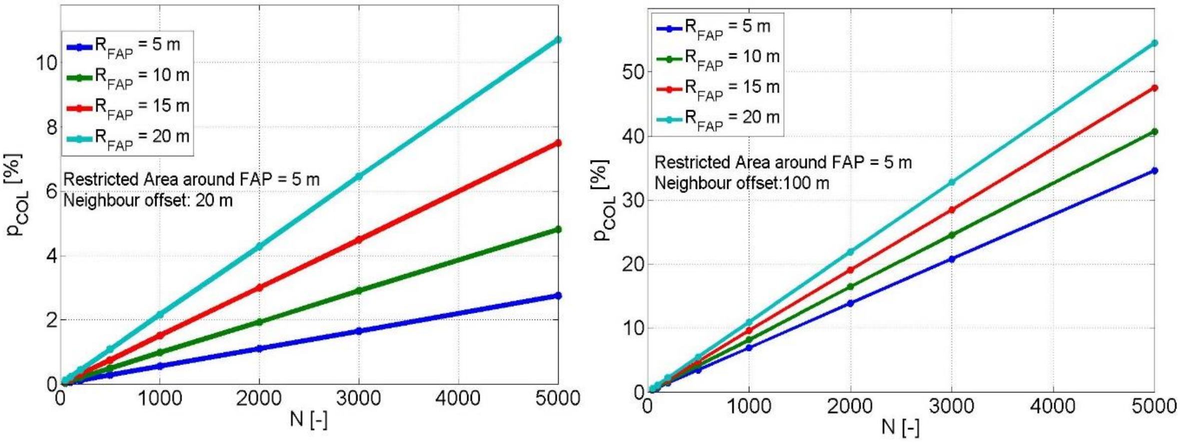

Figure 4.2 RANDM – Probability of collision to number of FAPs, offset 20/100 m.

The offset of 100 m may resemble uncertainty in position of the femtocell because methods for accurate location of position e.g. by GPS has not to be available for FAPs inside buildings. Adding offset of 100 m, the p_{COL} raised to approximately 55 % for 5000 FAPs with radius 20 m, which is rapid surge unlike the first figure where adjacencies only by double of radius were assumed. The assignment of PCIs by random method in environment with previously mentioned parameters could be unreliable and may leads to high number of reconfiguration request, which cause the high overhead traffic and may results into unstable configuration scenarios.

Probability of confusion in Random Model. The probability of confusion, p_{CONF}, is more dependent on the number of neighbouring cells. Non-linear dependency of p_{CONF} for the newly deployed FAP is presented on the Figure 4.3. The degree of non-linearity is increasing with enlargement of the radius. The scenario, where 5000 FAPs with 20 m radius is already deployed within the macrocell and the new FAP is put to them at random position, reveals that probability of confusion is nearly 60 %. Concerning confusion issue, the PCI allocation only by random decentralized function is not suitable solution, because it may lead to high number of reconfiguration requests and potentially to endless loop of reconfigurations.

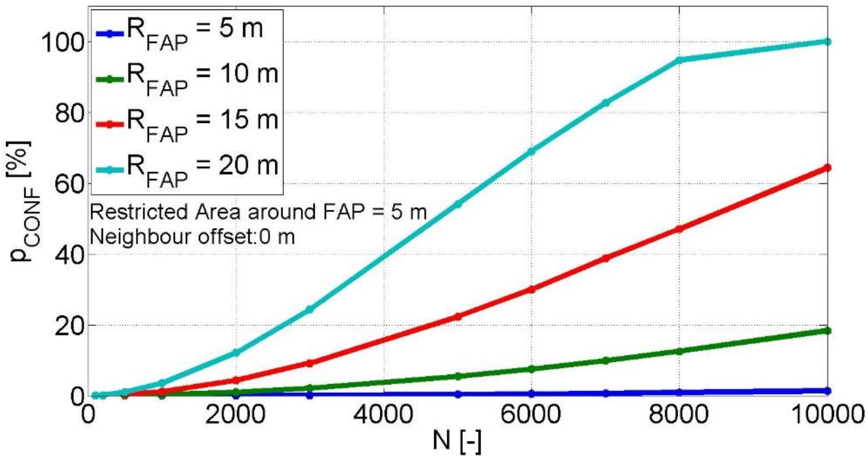

Figure 4.3 RANDM – Probability of confusion to N FAPs.

On the next picture, you can see composition of p_{CONF} as stated in chapter 3.5. The overall p_{CONF} is consisting of probability that the newly inserted cell can cause confusion, denoted *CC*, and may be confused, denoted *MBC*, from other cells. The first event, *CC*, may happen, when the newly emerged FAP select same ID as one of its second-level neighbours. It causes confusion to one of its direct-neighbours. The second case, MBC, happens when the new FAP emerge at such position, where some pair of their direct neighbours has not been adjacent before its appearance. The newly emerged cell may be in confusion situation.

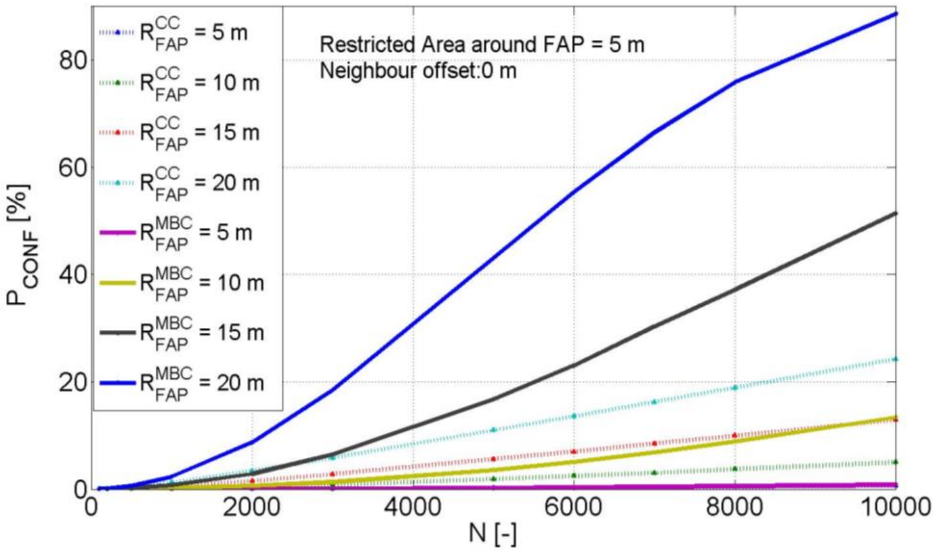

Figure 4.4 RANDM – Composition of probability of confusion to N FAPs.

The figure shows that main contribution to the p_{CONF} is from the cases, where the newly emerged FAP may be in confusion, *MBC*. The probability that the newly FAP cause confusion is approximately four times higher than for the probability that it can cause confusion.

Probability of intersection in Random Model. The Figure 4.5 depicts the probability of intersection, p_I, for different femtocells surfaces, ts_{FAP}, and different number of femtocells N. The surface without intersections taking into account is considered. All curves are more or less similar no matter what the number of femtocells is. The surface is computed for different R_{FAP}/R_M ratios. Actually, the different dependencies of p_I to R_{FAP}/R_M and p_I to N are transformed and replaced by one dependency, which respects the change of both parameters, N and R_{FAP}. The growth of the probability is small until ts_{FAP} equals to about 4×10^4 m^2. This part of graph corresponds to scenarios with either very small number of FAPs or/and small values of R_{FAP}. The major growth of the probability is in the interval from 4×10^4 to 10^6 m^2 where all curves can be approximated by the line with the gradient 0.65. In this interval, analytical expression of p_I can be derived as:

$$p_I = 0.65 \times \log_{10}(ts_{FAP}) - 2.88 \tag{20}$$

where ts_{FAP} is summary of surface of all cells without intersection. The standard deviation for gradients in this section is 0.03. The last part of graph, the surface of FAPs above 10^6 m^2 again results in a negligible increase of p_I. This section of graph corresponds to scenario when a macrocell becomes saturated with femtocells and it is nearly impossible introduce a new femtocell that would not overlap with one or more already deployed femtocells.

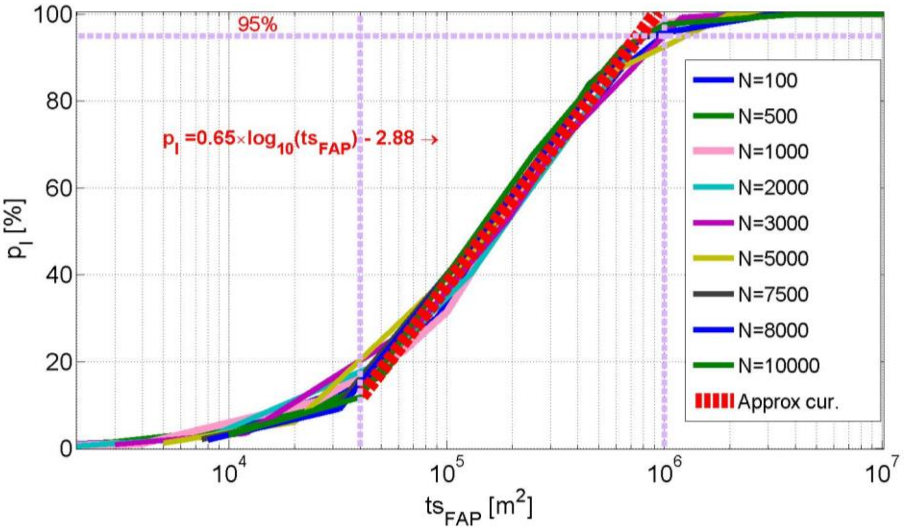

Figure 4.5 RANDM – Probability of intersection to different femtocell surfaces.

The previous graph shows that the number of femtocells is not important and only the total surface of femtocells plays the main role. Since the surface can be computed without considering the all intersections, which considerably simplify the computation process, it may serve as the indicator of saturation in a macrocell.

The total surface occupied by *N* femtocells, ts_{w0}, without considering their mutual overlapping is calculated using equation:

$$ts_{wO} = \sum_{i=1}^{N} \pi * (R_{FAP}^{i})^2 \tag{21}$$

Thus, the ratio of FAPs which meets the definition of adjacency to overall number of FAPs multiplied by the surface of the macrocell gives estimation of overlapping femtocell surface ts_O:

$$ts_O = \frac{N(adj)}{N} * S_M \tag{22}$$

where *N(adj)* represents number of FAPs meeting definition of adjacency, *N* is total number of FAPs and S_M is the macrocell surface.

The graph on the Figure 4.6 shows dependency of number of FAP to p_I. Otherwise said, the probability that a femtocell will have at least one neighbouring cell, when is randomly deployed in a network.

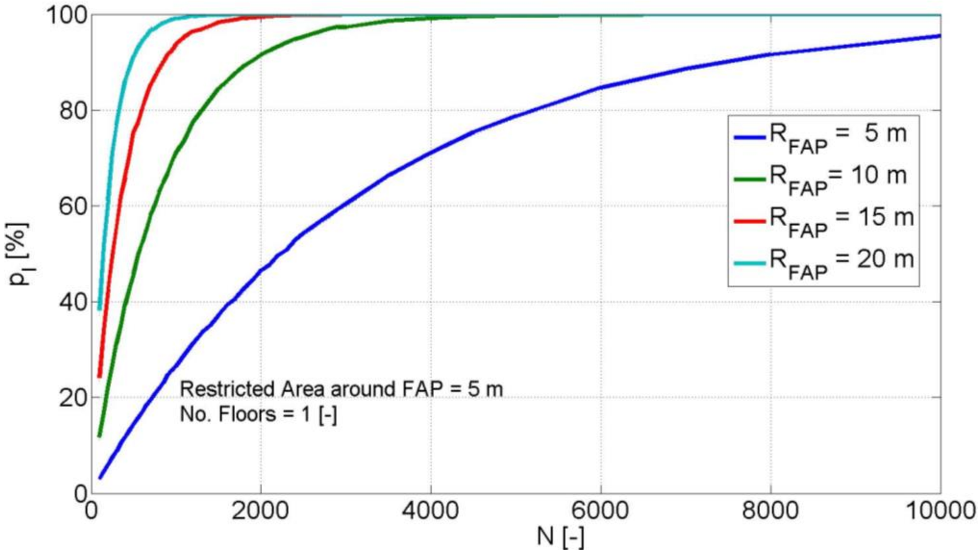

Figure 4.6 RANDM – Probability of intersection to number of FAPs.

As can be seen from the figure, for $R_{FAP} = 5\ m$, the p_I increases much slowly than for higher values of femtocell radii. Numerical values of p_I from the graph above are presented in the Table 4-1.

Table 4-1 Selected values of p_I for different number of femtocells and radius..

p_I [-]		**Radii of femtocells – R_{FAP} [m]**			
		5	**10**	**15**	**20**
Number of FAPs - N	100	0.03	0.12	0.24	0.38
	250	0.07	0.27	0.50	0.71
	500	0.14	0.46	0.75	0.91
	1000	0.27	0.71	0.94	0.99
	2000	0.47	0.92	1.00	1.00
	3000	0.60	0.97	1.00	1.00
	4000	0.71	0.99	1.00	1.00
	5000	0.79	1.00	1.00	1.00
	10000	0.95	1.00	1.00	1.00

The Table 4-2 lists Pearson's correlation coefficients *R* for the different curves of probability of intersection to R_{FAP}/R_M ratio (the subscripts in the table indicates the number of femtocells that is used as the parameter to calculate the coefficients). The missing values represent data that is irrelevant to the testing hypothesis of no correlation. The table can be read either by rows or by columns. For example second row (R_{500}) and the fourth column (R_{1000}) forms the correlation coefficient $R_{500\text{-}1000}$, which equals to 0.98.

These coefficients indicate strength of dependency between particular p_I curves, i.e. the value of one means that there are identical curves, respectively the value of zero indicates completely different curves. As it can been observed, the strongest dependency is naturally between identical curves (the correlation coefficient $R_{100\text{-}100} = 1$) and the coefficients decreasing with increasing *N*. The correlation coefficient $R_{100\text{-}5000}$ is only 0.64 that represents not so strong dependency. Notice that although every of p_I curves are calculated for differently positioned femtocells, there is the dependency between the resulting probabilities. In other words, the value of probability for N_k can be also estimated from a p_I curve calculated for N_m but both, N_k and N_m, have to be closed each other. The correlation coefficients also reveal that probabilities are gradually changing with increasing *N*, which means there is no scenario, where the probability would abruptly change.

Table 4-2 Pearson's correlation coefficients for p_I

	R_{100}	R_{500}	R_{1000}	R_{2000}	R_{3000}	R_{5000}	R_{7500}	R_{8000}	R_{10000}
R_{100}	1	0.90	0.83	0.76	0.71	0.64	-	-	-
R_{500}	0.90	1	0.98	0.94	0.90	0.82	0.74	0.73	0.69
R_{1000}	0.83	0.98	1	0.98	0.95	0.88	0.81	0.81	0.77
R_{2000}	0.76	0.94	0.98	1	0.99	0.95	0.90	0.89	0.86
R_{3000}	0.71	0.90	0.95	0.99	1	0.98	0.95	0.94	0.91
R_{5000}	0.64	0.82	0.88	0.95	0.98	1	0.99	0.99	0.97
R_{7000}	-	0.74	0.81	0.90	0.95	0.99	1	1.00	1.00
R_{8000}	-	0.73	0.81	0.89	0.94	0.99	1.00	1	1.00
R_{10000}	-	0.69	0.77	0.86	0.91	0.97	1.00	1.00	1

Cumulative Distribution Function in the Random Model. The Figure 4.7 shows Cumulative Distribution Function (CDF) of neighbouring FAPs for 4 selected ratios of FAP radius to a macrocell radius (R_{FAP}/R_M) and 8000 FAPs. The cumulative distribution function is obtained from the vector of intersecting cells. The length of vector corresponds to the number of iterations in Monte Carlo method. Each element of the vector represents the number of femtocells, which intersects with the newly introduced femtocell at one iteration. The CDF shows the probability that newly introduced cell will have up to the number of neighbours.

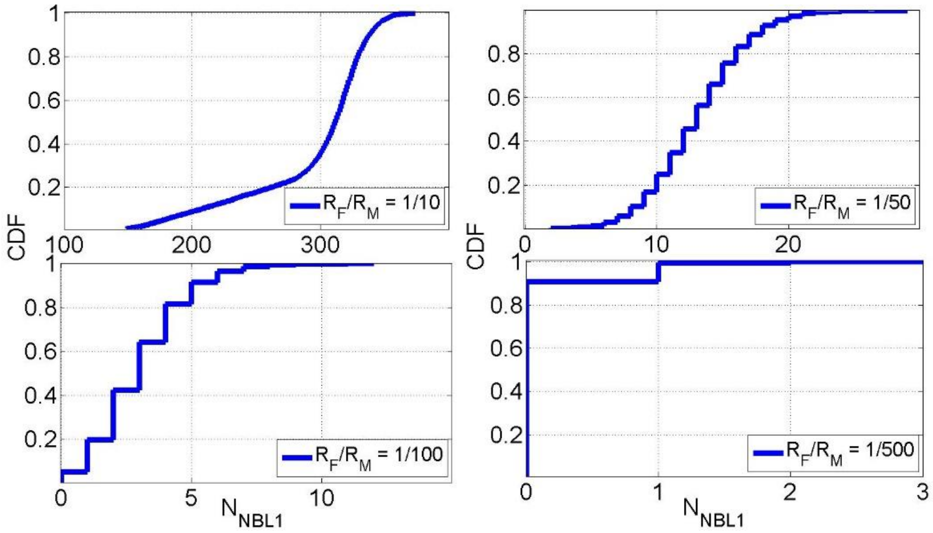

Figure 4.7 RANDM – Cumulative distribution function of neighbouring FAPs, N 8000.

The graphs represents how the ratio of the macrocell area to the femtocell area influences number of neighbours, when the number of FAPs is preserved and only the radius, or more generally neighbouring function, is changed at the same. It can be seen that for smaller ratios, there is a lower threshold of neighbouring FAPs, which means that the new FAP cannot be placed to have a less neighbours than this threshold is.

If the previous characteristics of cumulative distribution function are differentiated then the probability density for number of neighbouring cells will be obtained. The probability density shows the probability level that the newly introduced cell will have the exact number of neighbours and you can see it on the Figure 4.8. The picture illustrates the Probability Function of the number of neighbours (PF_{NEIGHB}) for selected scenarios (i.e. the probability that the newly introduced FAP will have exactly the *K* number of neighbours). It is obvious that the number of neighbours grows together with increase of R_{FAP} and the increment is approximately double of the previous value. Moreover, it can be observed that kurtosis and skewness of the probability distribution is changing. Increase of radius means kurtosis is decreasing, otherwise said the distribution become larger. It signifies that the randomly emerged FAP will have very different number of neighbours and the prediction of the number of neighbours for new random cell has to be done from wider range.

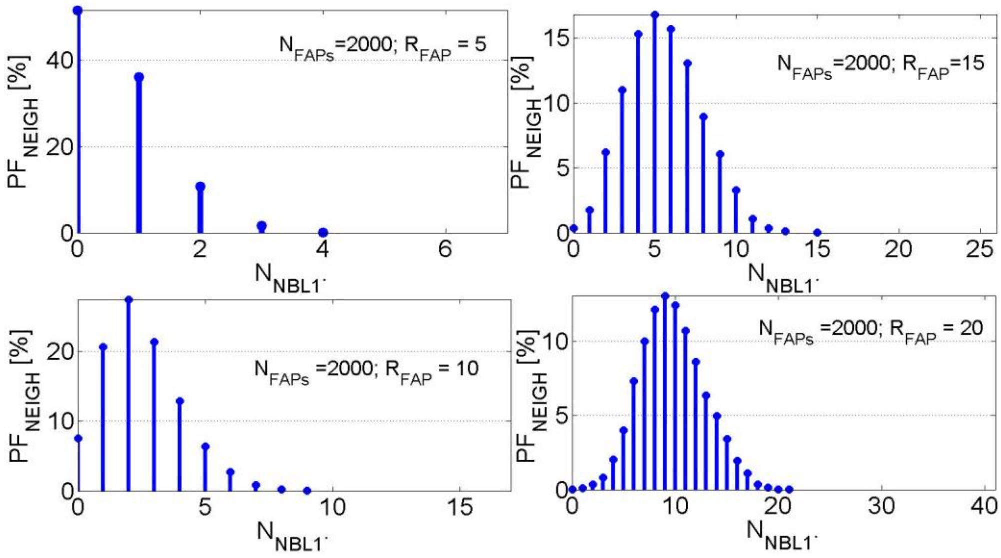

Figure 4.8 RANDM – PF_{NEIGHB} for one-hop neighbours.

Comparison calculation to simulation results. The probability of confusion was evaluated by aforementioned equations and by simulations. Simulation case means that every of *n* Monte Carlo iterations was analysed and number of confusions recorded, nothing was computed. The contrast between calculated and simulated results is shown on the next picture, Figure 4.9. The variation of simulations from calculations is negligible and it can be assumed that with increasing number of iterations it will converge. Therefore, it is obvious that proposed simulation and derived equations are conformable. The values of confusion mainly depend on the cell radius and the number of deployed cells. Except beginning and end of running, there is linear dependency. In case scenario with 10 000 femtocells with 20 m radius, the confusion is 100 %.

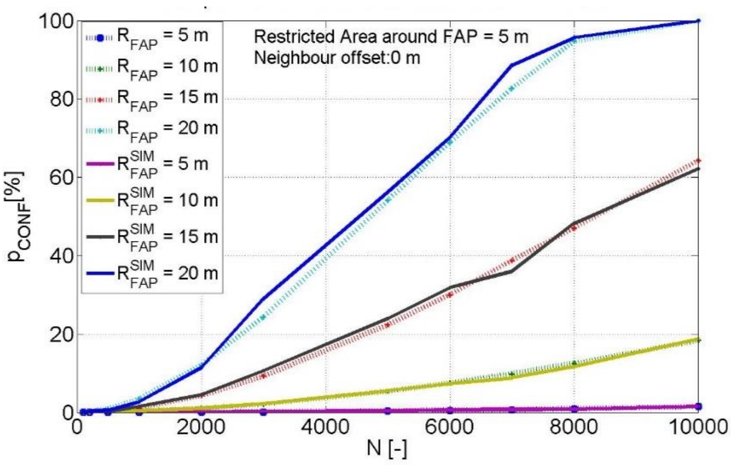

Figure 4.9 RANDM – p_{CONF}, comparison calculated vs simulated outputs.

4.2 Dense Urban Model – distance based neighbourhood

Results obtained from the DUM are presented in this part of my thesis. The adjacency is considered only by the distance criteria, which is idealised case neglecting attenuation of walls in this section. The main purpose of such schema is to study only impact of topology change from RANDM. The visualization of neighbourhood relation can be found on the Figure 4.10.

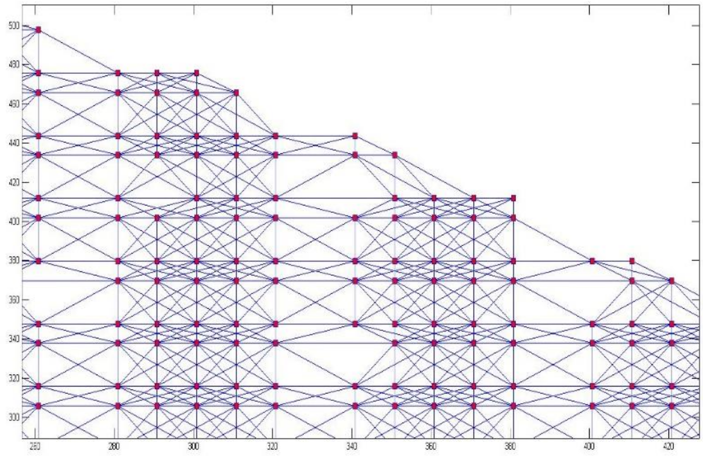

Figure 4.10 DUM – Visiualization of neighbourhood relations.

This model has constraint in the maximum number of cells, which can be active inside the macrocell. The maximum number of slots available for FAPs is influenced by the street width. There are 6739 predefined slots for model with the street five meters wide, for 10 m, it is 5223, for 20 m, it is 3407, and for 40 m, it is 1800 slots. Therefore, the comparison with other figures has to be done for corresponding values and may not possible for higher number of femtocells.

Probability of collision in Dense Urban Model (distance based). The probability of collision with the street 5 and 40 m wide at different cells radius is shown on the Figure 4.11. As well as in the RANDM, there is strong linear dependency of the probability of collision to the number of FAPs. The probability takes the similar values as in the RANDM with neighbourhood relation determined by double of cell radius.

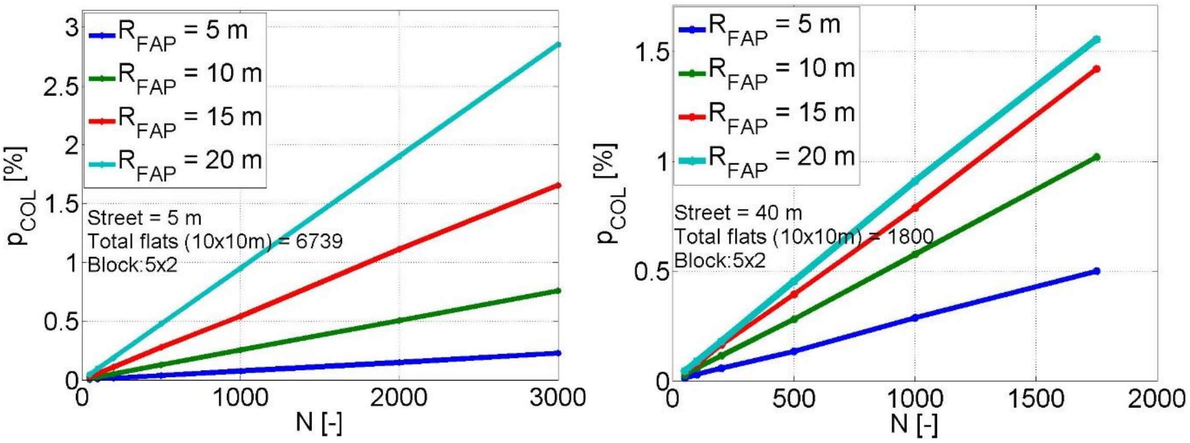

Figure 4.11 DUM – Probability of collision to number of FAPs with street 5 m / 40 m.

If the street width is increased to 40 meters, it may be anticipated that the p_{COL} will be lower, but simulation shows opposite results. The value of the probability of collision with the street 40 meters is similar or slightly higher than for 5 meters. It is because collision is dependent only to direct neighbours. Despite the number of possible neighbours from different blocks drops with increase of the street width, the extension of the street reduces the number of possible femtocell slots at the same time. It leads to more dense deployment of femtocells. As result of this, collision happens more frequently inside the block. Otherwise said, when the street is five meters wide then the macrocell can contain maximum 6739 femtocellular slots, which means that for 1000 FAPs the occupancy of all slots is around 15 % but with the street 40 meters wide there is 55 % occupancy of all slots.

Dependency of the p_{COL} to the street width is shown on the Figure 4.12. The figure has the number of FAPs N inside the macrocell put as the parameter. The coverage radius is set to ten meters. As mentioned earlier, the probability is in positive correlation with the street width.

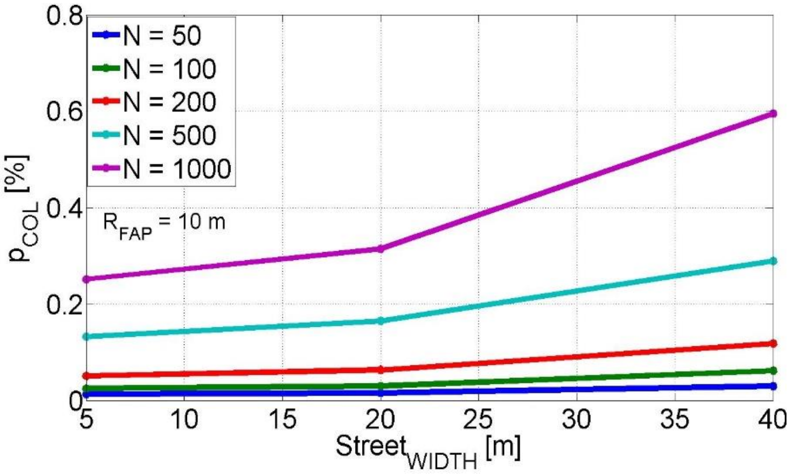

Figure 4.12 DUM – Probability of collision to street width for R_{FAP} = 10m.

Probability of confusion in Dense Urban Model. Another studied issue is the confusion. As well as in the RANDM, the results from the DUM were compared with simulations. Simulations were carried out the same way as in the RANDM. The resulted graph can be found on the next picture. There it can be observed that simulations are comparable to calculated values for all radii. Maximum achievable value of confusion is 55 % for scenario with 5000 femtocells and 20 m radius. The value of 100 % is not achieved because DUM has limitations in maximal number of deployed cells under defined macrocell.

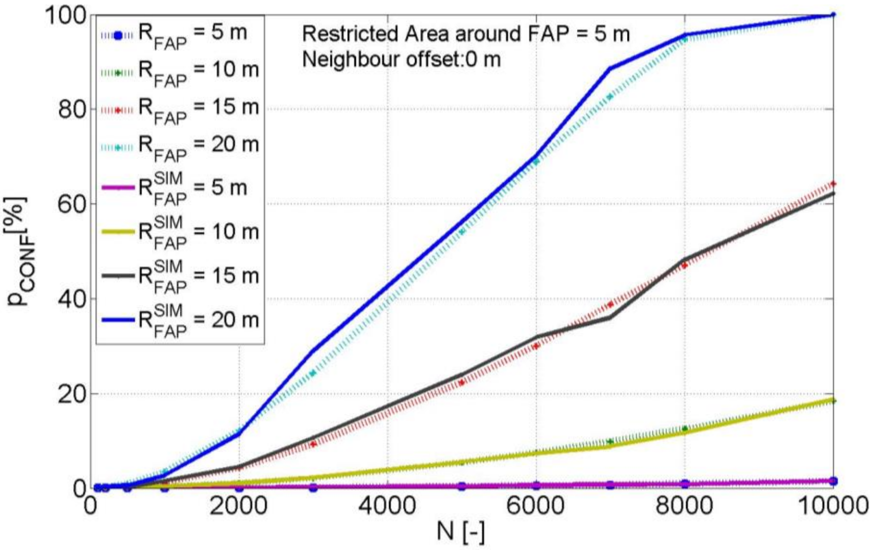

Figure 4.13 DUM – p_{CONF}, comparison calculated vs simulated outputs.

The following graph shows composition of the p_{CONF} for the DUM in term of the two events: the newly emerged cell may be confused, denoted MBC, or can cause confusion, denoted CC. This is the similar of the Figure 4.4 depicted for the RANDM.

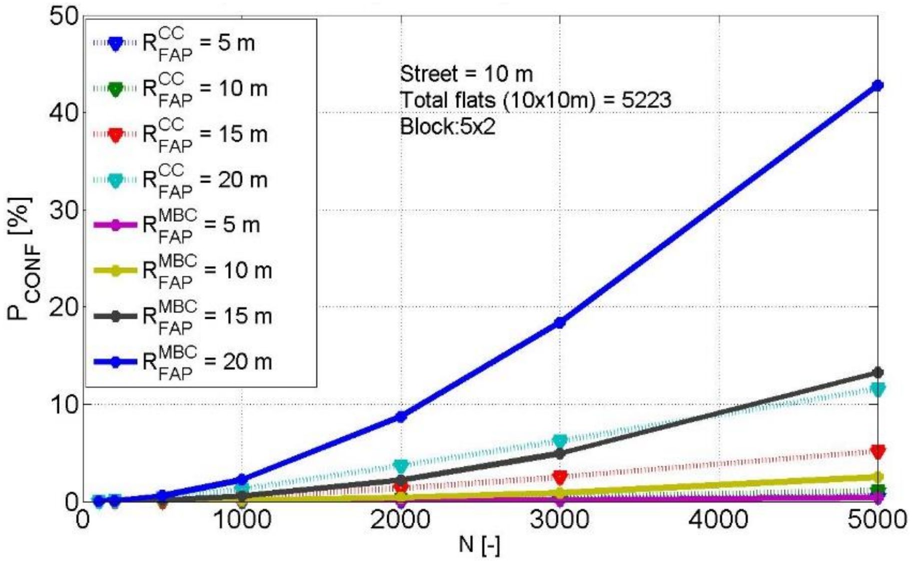

Figure 4.14 DUM – Composition of probability of confusion to N FAPs.

It can be concluded that composition is the same as for the RANDM. The main component of the p_{CONF} is caused by the probability that the newly emerged cell may be confused by other cells.

Probability of intersection in Dense Urban Model (distance-based). The last graph in this sub-chapter is the p_I. It depicts how often the newly deployed FAP is in a relation with any other FAPs. It is the counterpart of the Figure 4.6 but for the DUM with distance-based adjacency.

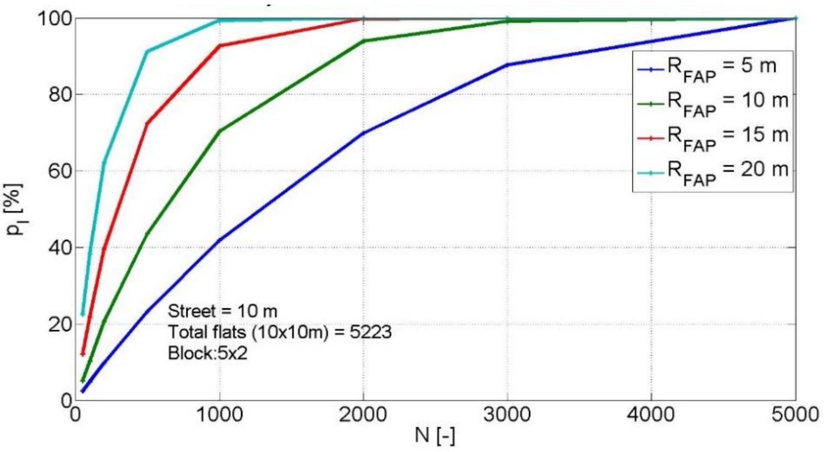

Figure 4.15 DUM – Probability of intersection to N FAPs, distance based.

The picture shows similar results as in the case of RANDM, except the curve for RFAP equal to five meters. In the case, the p_I achieves value of 100 % sooner, for less than half of pre-deployed FAPs contrary to the RANDM.

4.3 Dense Urban Model – neighbour-list based adjacency

Neighbour-list adjacency is based on predefined relations as shown in the Figure 3.4. There are two variants, the first referred as R_A where every FAP has maximum of four neighbours, and the variant R_B, where a FAP has six or eight neighbours depending its position inside a block. The purpose of that way determined adjacency is to study not only topology change but also include effect of different adjacencies. Different neighbourhood relation definitions should emulate the fact that a signal propagates better through windows than through walls inside a block.

Probability of collision in Dense Urban Model (neighbour-list based). The following figure shows probability of collision for neighbour-list variant R_A, R_B. It is observed, that the p_{COL} is lower in comparison to the DUM with distance based neighbourhood relation, but the linear dependency persists. Values of the p_{COL} are insignificant and random assignment of Physical Cell Identity could be considered as viable in this scenario.

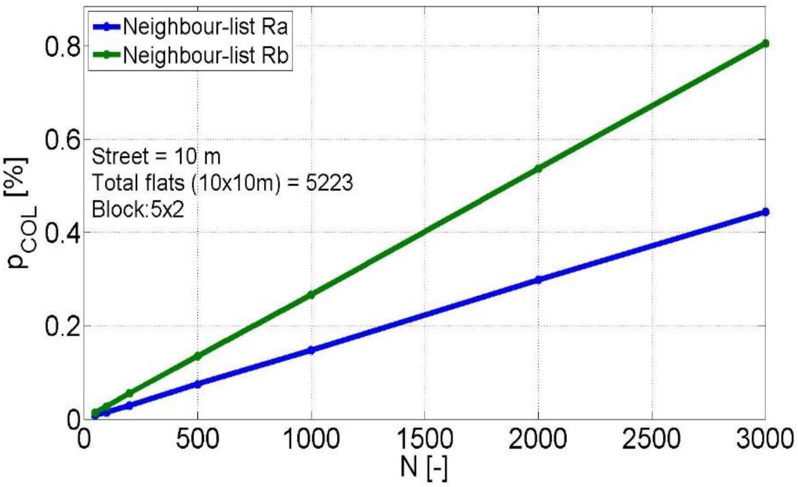

Figure 4.16 DUM – Probability of collision to number of FAPs, neighbour-list based.

Probability of collision in Dense Urban Model (neighbour-list based). As the neighbour-list variant in the DUM uses constrained neighbourhood definitions, it results in limited number of second-level neighbours. Comparison of the p_{CONF} in the DUM with adjacency defined by neighbour-list to the p_{CONF} with adjacency defined by the distance, I find out that curve of neighbour-list R_A corresponds to running for femtocells with radius of five meters. Values of the p_{CONF} for scenarios with neighbourhood defined by neighbour-list R_B are nearly three times higher but it does not correspond to running of radius 10 m in DUM where the adjacency is appointed by the distance. Generally, the values of p_{CONF} are negligible in term of random PCI assignment for these two cases. The values of p_{CONF} can be seen on the next picture.

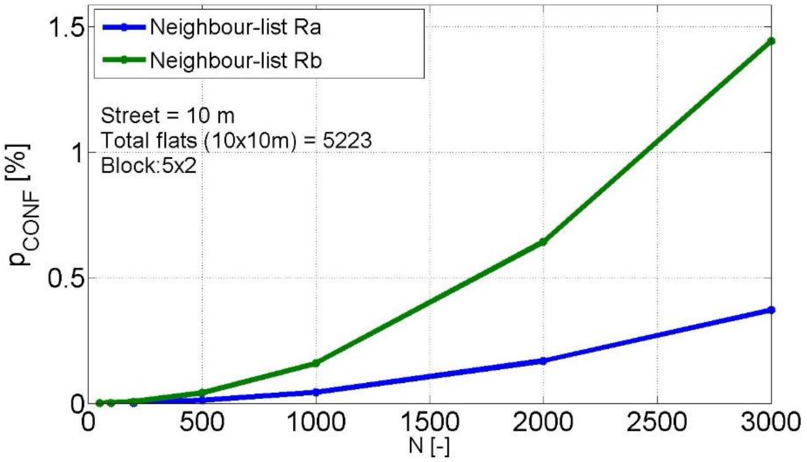

Figure 4.17 DUM – Probability of confusion to number of FAPs, neighbour-list method.

This output can also shows that certain topology may mitigate the p_{CONF} when limited number of potential adjacencies may arise. It means if propagation of signal from a FAP would be strictly limited, that confusion and collision can be very rare as is obvious from the Figure 4.17.

Probability of intersection in Dense Urban Model (neighbour-list based). The following graph depicts p_I for the DUM with neighbour-list based adjacency.

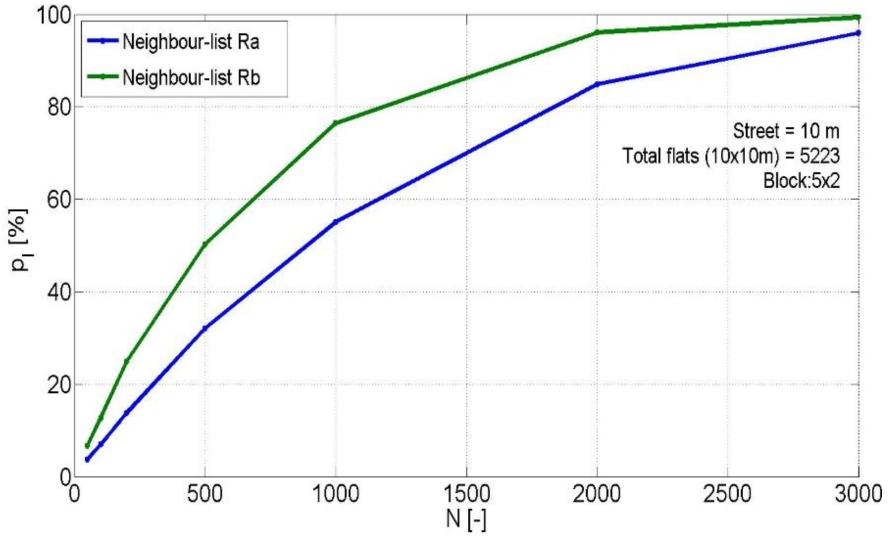

Figure 4.18 DUM –Probability of intersection to N FAPs, neighbour-list based.

The picture illustrates that the p_I of nearly 100 % is achieved around 3000 FAPs regardless the difference of applied neighbour-list methods. However, for lower values of the p_I, the curves have different running for each variant, R_A and R_B. This graph is counterpart for charts on the Figure 4.6 and the Figure 4.15 but for DUM with neighbour-list based adjacency.

4.4 Random and Dense Urban Model comparison

This section is devoted to comparison the outputs from the DUM with neighbour-list based adjacency to the RANDM. On the next picture, you can see dependency of the p_{COL} *to* N FAPs for both the RANDM and the DUM. Based on the findings, it can be concluded that the variant R_B corresponds to the RANDM where FAPs have radius 10 m. The variant R_A does not correspond to the RANDM with the radius five meters as it may be expected because obtained results are above them. Consequently, for the femtocell with radius of five meters, the neighbour-list method has to be defined thus that femtocells would have less than four neighbouring cells on average.

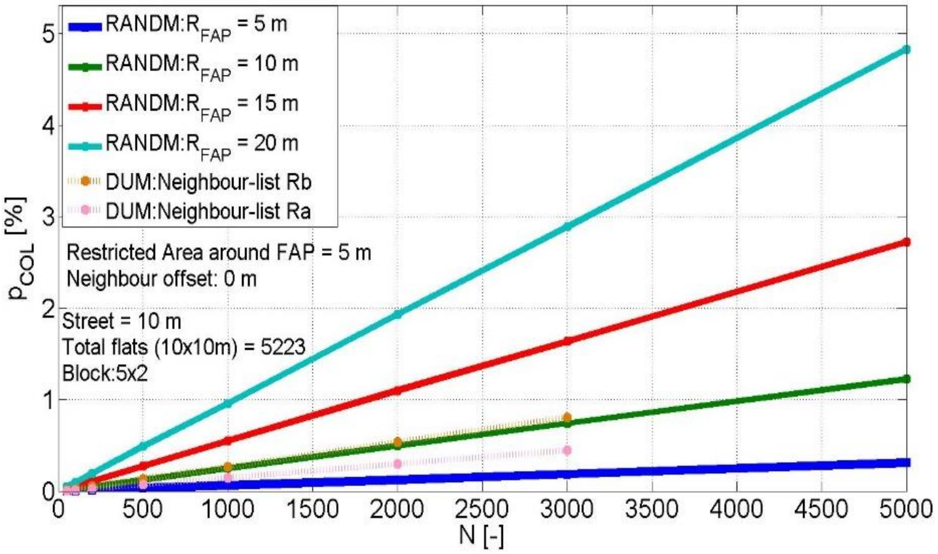

Figure 4.19 Comparison of probability of collision between RANDM and DUM.

The next graph shows comparison of results between the RANDM and the DUM for the probability of confusion. As expected, the findings are the same as in the previous case. The neighbour-list method R_B corresponds to radius 10 m and the variant R_A is slightly above the results for scenario with radius of femtocells set to five meters.

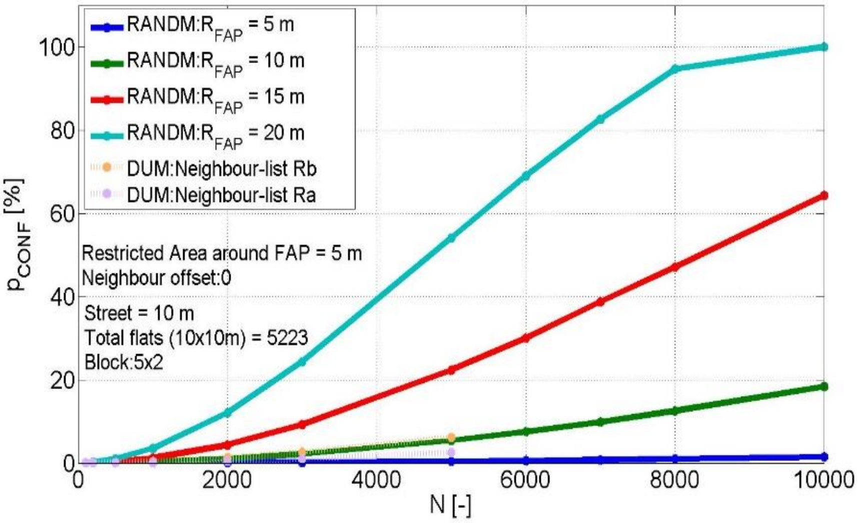

Figure 4.20 Comparison of probability of confusion between RANDM and DUM.

These outputs show the correlation between results from the DUM with neighbour-list adjacency and the RANDM with distance based neighbourhood. Similarly, it can be derived another neighbour-list variant for other radii, because there is shown only that the variant R_B corresponds to R_{FAP} equal to 10 m. It may help create interchangeable models or appoint conditions when some model can be replaced by another one.

4.5 Clusters in Random model

This section presents and discusses obtained results of cluster evaluations. All simulations and evaluation were conducted only in the RANDM, because for the DUM it is pointless. The Figure 4.21 shows number of clusters for different number of FAPs per the macrocell and for different femtocell radius (R_{FAP}). As it can be observed, the number of clusters exponentially increases until the number of FAPs reaches a threshold, N_{FAPs}^{Tresh}, which depends on R_{FAP}. For example, assuming $R_{FAP} = 10$ m, respectively $R_{FAP} = 5$ m, N_{FAPs}^{Tresh} corresponds to about 1000 FAPs, respectively 5500 FAPs. Once the number of FAPs exceeds N_{FAPs}^{Tresh}, standalone clusters begin to merge, i.e. there is less number of clusters, but clusters become bigger and composed of much more femtocells.

From the point of collision and confusion events, a cluster can be viewed as an independent group of FAPs. It means that these issues can be solved in a cluster independently to other clusters. However, once the threshold the N_{FAPs}^{Tresh} is exceeded, clusters start merging and thus bigger area and number of FAPs are affected when solving these events. Therefore, the issue becomes more complex after the threshold.

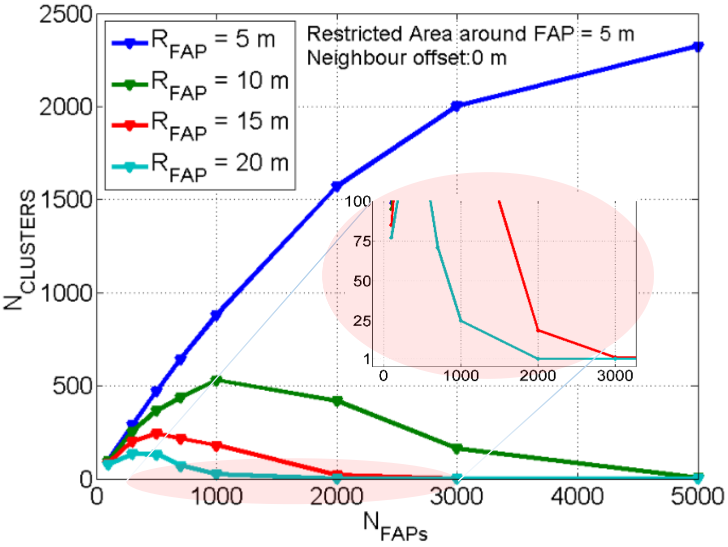

Figure 4.21 $N_{CLUSTERS}$ to N_{FAPs} and R_{FAP}.

The minimum and maximum graph density, GD, per clusters is shown in Table 4-3. In the case, the *GD* is equal to one a cluster is fully saturated, i.e. the cluster represents a full mesh topology. Contrary to expectations that the upper bound of GD should grow with increasing number of FAPs and FAP radius, the upper bound of GD is decreasing. As clusters increase in their sizes and decrease in their numbers, a cluster with full meshed topology is nearly impossible to achieve, because more and more distant FAPs are the part of the cluster. For example, to form the full mesh topology with 1000 FAPs, nearly half million edges would be needed with FAP radius corresponding to the macrocell radius.

Table 4-3 Minimal and maximal GD per clusters

N_{FAPs}	**R_{FAP}=5 m**	**R_{FAP}=10 m**	**R_{FAP}=15 m**	**R_{FAP}=20 m**
100	0 – 1	0 – 1	0 – 0.5	0 – 0.5
300	0 – 1	0 – 0.667	0 – 0.333	0 – 0.222
500	0 – 0.5	0 – 0.321	0 – 0.219	0 – 0.096
700	0 – 0.667	0 – 0.25	0 – 0.156	0 – 0.029
1000	0 – 0.5	0 – 0.222	0 – 0.022	0 – 0.0055
2000	0 – 0.333	0 – 0.042	0 – 0.003	0.0048
3000	0 – 0.25	0 – 0.009	0.0027	0.0048
5000	0 – 0.137	0 – 0.001	0.0027	0.0048

An interdecile range, *IDR*, is used to evaluate difference between cluster sizes statistically. The smaller *IDR* is, the smaller variance in cluster size is, and vice versa. Better insight into FAPs placement in the network can be obtained when taking into account the number of clusters and IDR. It enables to optimize PCI assignment process. For example, if values of R_{FAP} = 20 m and N_{FAPS} = 1000 are assumed then $N_{CLUSTERS}$ equals to 25 (see the Figure 4.21) and $IDR_{SIZE\text{-}CLUSTERS}$ equals to seven (see the Figure 4.22). This means that 80 % of all clusters differ in size only about seven FAPs. In other words, majority of clusters have very similar sizes and the same PCI assignment process can be applied in all clusters. The Figure 4.22 also shows that IDR has a global maximum that depends on R_{FAP} values. For bigger R_{FAP} values, the global maximum occurs at the smaller number of N_{FAPs}. Once the global maximum is reached, existing clusters in the macrocell merge into a big cluster, i.e. the PCI assignment process has to be managed over the whole macrocell instead of locally independent areas.

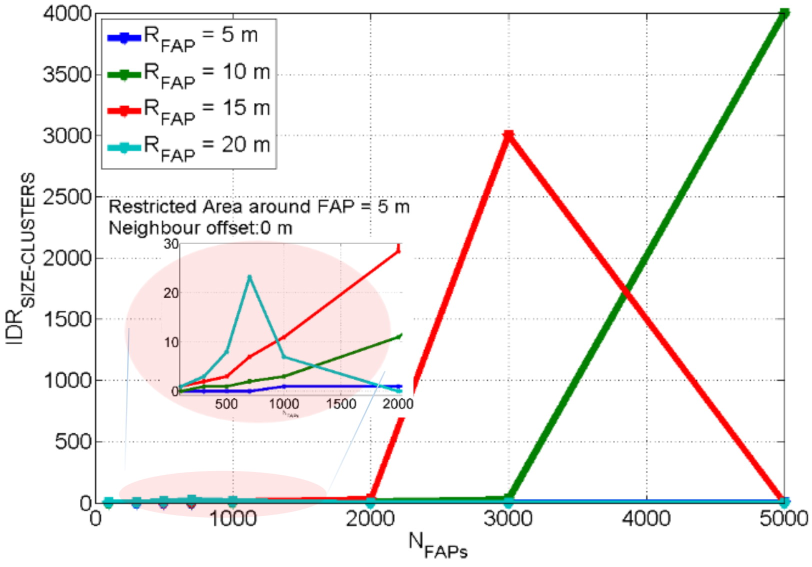

Figure 4.22 IDR of cluster size for different N_{FAPs} and R_{FAP}.

Other parameter that I used in my thesis is the maximal degree of vertex, δ. The maximal degree of vertex represents maximal number of neighbours in a cluster. The δ is related to chromatic number of cluster, χ. Value of χ indicates the minimum number of PCIs that has to be used in a given cluster. The value χ is known in advance for a certain type of graphs (e.g., bipartite, star or cycle graphs), but to obtain the chromatic number for an arbitrary graph it is NP-complete problem. Although the computation of the chromatic number is complex task, the upper bound of χ can be easily found out using δ. The interdecile range of max degree ($IDR_{MAX\text{-}DEGREE}$) in a cluster is used to evaluate the dispersion of maximum δ statistically. The $IDR_{MAX\text{-}DEGREE}$ determinates difference of minimal PCI subsets needed to ensure proper PCI assignment in the clusters. In case of small $IDR_{MAX\text{-}DEGREE}$, the subsets for all clusters can be nearly identical. On the contrary, as $IDR_{MAX\text{-}DEGREE}$ grows, required PCI subsets will be very dissimilar in different clusters.

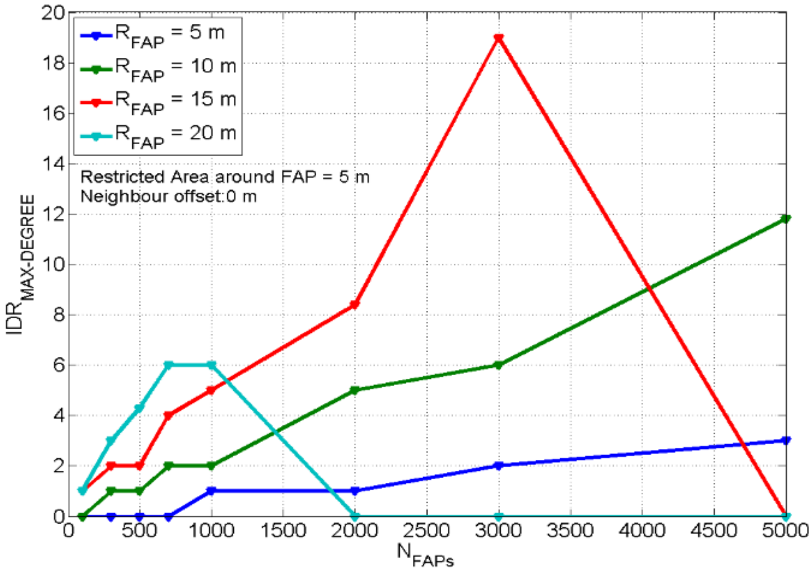

Figure 4.23 IDR of maximal degree in clusters for different N_{FAPs} and R_{FAP}.

The worst-case scenario has to be considered from the point of the PCI assignment process, when introducing the new FAP among *N* other existing FAPs. It occurs when the new FAP have neighbourhood with the maximum number of FAPs. Since, every of direct neighbours should have different PCI to be considered as properly configured, it means that the PCI set for the new FAP has to be constrained about all of those PCIs of the one-hop and two-hop neighbours.

The maximal number of a first-hop (L1) and second-hop (L2) neighbours, $N_{NBmax(L1/L2)}$, is illustrated in the Figure 4.24. It shows worst-case scenarios under defined conditions.

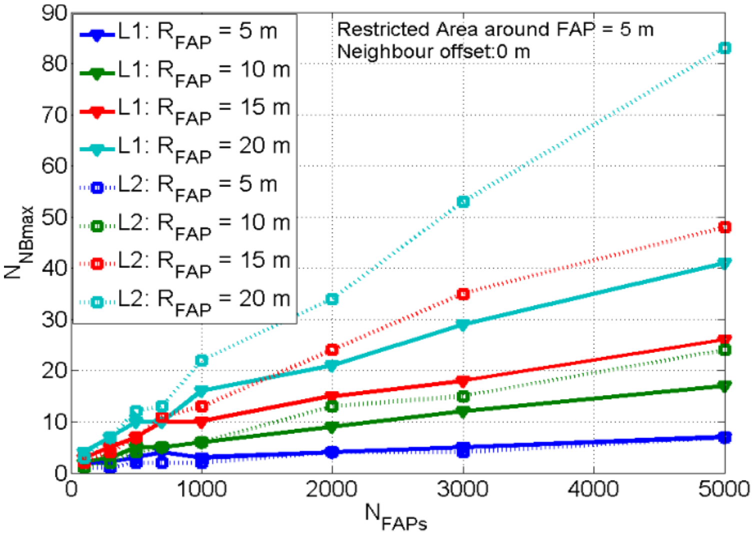

Figure 4.24 Maximal number of first-hop and second-hop neighbours (L1, L2).

As shown on the picture above, the newly inserted FAP among 5000 randomly placed FAPs with R_{FAP} 15 m has 28 one-hop neighbouring cells at most, which is much less than the number of available PCI identities. Even splitting of PCI set to different subsets for CSG cells, macrocells provide sufficient PCI space at abovementioned circumstances in the network. Maximal number of neighbouring cells is the worst-case scenario and algorithm on assignment of PCI must be prepared to solve it.

The Figure 4.25 shows, the opposite situation, i.e. a minimal number, of first-hop and second-hop neighbours, $N_{NBmin(L1/L2)}$. For small values of R_{FAP} or small number of FAPs, the new FAP can be placed in such way that this FAP will have no neighbour at all. However, the figure shows that there is the threshold above which it is impossible to place the new FAP without having one or more neighbours. For example, in case R_{FAP} = 20 m, respectively 15 m, the threshold corresponds to 2000 FAPs, respectively 3000 FAPs.

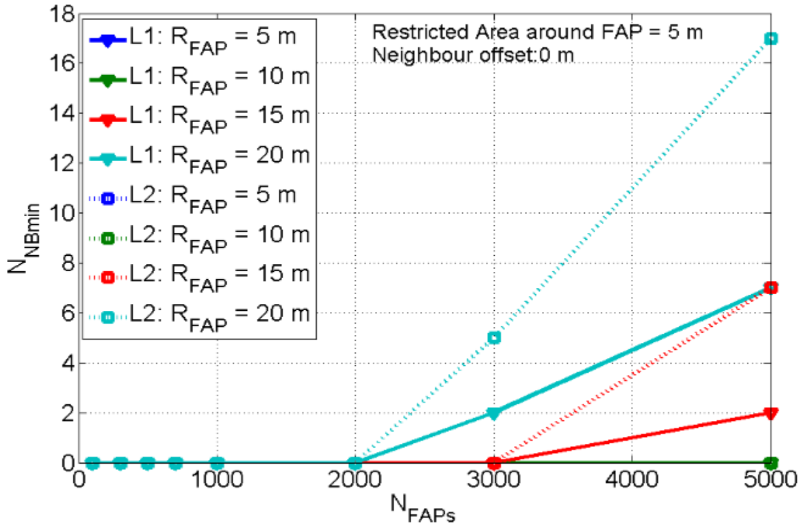

Figure 4.25:Minimal number of first-hop and second-hop neighbours (L1, L2).

Finally, Figure 4.26 indicates the most frequent number of first-hop and second-hop neighbours, $N_{NB(L1/L2)}$. These are values that most of femtocells may expect when introduced between N_{FAPs}. For example one-hop neighbours, $N_{FAPs} = 2000$ FAPs and $R_{FAP} = 20$ m, $N_{NBminL1} = 0$, $N_{NBL1} = 9$, and $N_{NBmaxL1} = 21$.

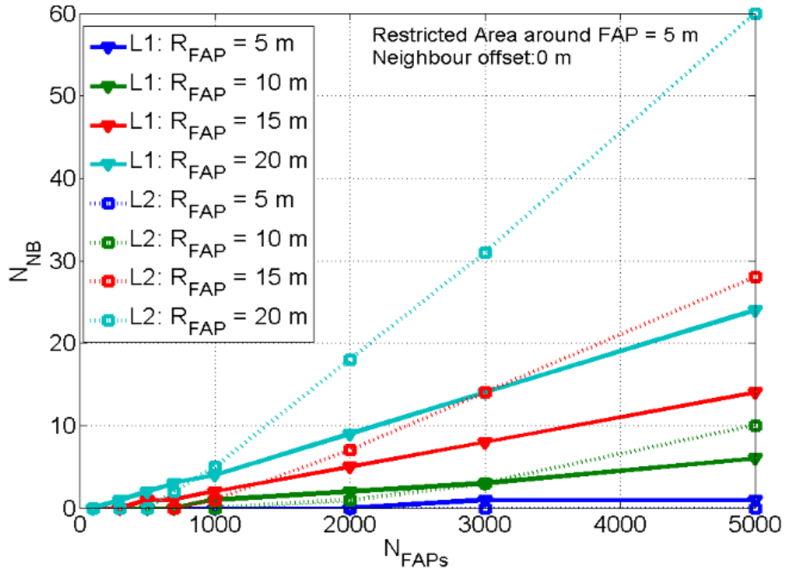

Figure 4.26 Most frequent number of neighbours in first and second level.

The Table 4-4 summarizes selected results from clusters evaluations. The left most column denotes parameters used in a particular evaluation of RANDM. Other columns resemble chosen indicators with result values for a scenario.

Table 4-4 Summary – results related to clusters

Scenario	**$IDR_{SIZE-CLUSTERS}$**	**$IDR_{MAX-DEGREE}$**	**$N_{CLUSTERS}$**
N_{FAPs}=500, R_{FAP}=10 m	1	1	366
N_{FAPs}=1000, R_{FAP}=10 m	3	2	529
N_{FAPs}=5000, R_{FAP}=10 m	3912	11.8	7
N_{FAPs} =500, R_{FAP} =15 m	3	2	242
N_{FAPs}=1000, R_{FAP}=15 m	11	5	179
N_{FAPs}=5000, R_{FAP}=15 m	0	0	1
N_{FAPs} =500, R_{FAP} =20 m	8	4.3	132
N_{FAPs}=1000, R_{FAP}=20 m	7	6	25
N_{FAPs}=5000, R_{FAP}=20 m	0	0	1

The table above shows that maximal value of IDR in size of clusters is nearly 4000, IDR of max-degree equal to 11.8 and most of clusters is created under condition of 1000 FAPs with 10 m radius.

The Table 4-5 bring together results of evaluations in RANDM in term of neighbouring cells. The first column indicates parameters of particular evaluations. The column $N_{NBmaxL1}$ denotes maximal number of one-hop neighbours, the columns $N_{NBL1} \leq X p_{90\%}$ and $N_{NBL2} \leq X\ p_{90\%}$ show upper bound of number of one-hop respectively two-hop neighbours at probability level 90 %. Otherwise, number of neighbours at particular level, which newly emerged FAP may expect in 90 % of cases.

Table 4-5 Summary – results related to inserting a new FAP.

Scenario	$N_{NBmaxL1}$	$N_{NBL1} \leq X$ $p_{90\%}$	$N_{NBL2} \leq X$ $p_{90\%}$
N_{FAPs}=500, R_{FAP}=10 m	5	2	1
N_{FAPs}=1000, R_{FAP}=10 m	6	3	2
N_{FAPs}=5000, R_{FAP}=10 m	17	9	14
N_{FAPs} =500, R_{FAP} =15 m	7	3	2
N_{FAPs}=1000, R_{FAP}=15 m	10	5	5
N_{FAPs}=5000, R_{FAP}=15 m	26	18	36
N_{FAPs} =500, R_{FAP} =20 m	10	5	4
N_{FAPs}=1000, R_{FAP}=20 m	16	8	11
N_{FAPs}=5000, R_{FAP}=20 m	41	30	66

The results indicates that for presented scenarios, the PCI range should be sufficient as at probability level there is maximum 30 and 66 neighbours in first respectively second level. Thus, a valid assignment with 96 PCIs should be possible in RANDM where 5000 FAPs is deployed in 90 % of cases.

4.6 Discussion

The evaluation of proposed models was performed in this section. I evaluated models for many possible combinations of parameters and only the distinctive graphs or pictures showing important results are mentioned in this chapter. At first simulation in the RANDM are stated and then results of the DUM are referred. Last part of simulations was aimed to study clustering of femtocell under random deployment. Since the definition of neighbourhood relation and models are independent on exact dimensions, all of these results can be expressed as ratio of macrocell coverage radius to femtocell coverage radius, as shown on the Figure 4.7.

The evaluation of RANDM shows that probability of intersection, collision and confusion is negligible up to 1000 cell for all radii. As specific propagation can greatly influence the exact values of the mentioned probabilities, I appoint offset of 20 and 100 m, which is added to neighbourhood relation function, which plot adjacency. The smaller value simulate safety margin to propagation conditions and the value 100 m resemble uncertainty in exact femtocell position. Under these assumptions, there is rapid surge of probability of confusion and collision.

Comparison with values without offset shows that precise localization of femtocell enables precise adjusting scheme of automated PCI assignment.

Based on knowledge of the total surface that is covered by femtocells within a macrocell, I derive an analytical expression that can be used to calculate the probability of intersection. The major role in this expression plays total surface of the femtocells inside macrocell computed without considering intersection, which can serve as indicator of femtocell environment in term of intersection probability.

Results from the DUM were evaluated for neighbourhood relations appointed by distance and neighbour-list method. It shows that a RANDM and DUM can be under specific conditions interchangeable. There is positive correlation between the street width and the probability of collision and confusion.

Moreover, comparison of simulation results and calculations were done on Figure 4.9 and Figure 4.13. It shows the both approaches coincide between themselves. The evaluation of RANDM to clusters reflects some important characteristic of randomly deployed cells, which can be used to analyse how difficult the automated PCI assignment would be. The graph on Figure 4.21 shows that exists certain threshold where merging of small clusters of femtocells tend to merge into bigger ones, which can negatively affect automated process of PCI allocation. The similarity of particular clusters can be caught by IDR and maximal and minimal degrees can be used to estimate number of required PCIs.

To sum it up, this chapter guide through analysis many different scenarios in two different models and propose some characteristics and limits important for automated PCI assignment.

5 Proposed framework on automated PCI assignment

Femtocells together with other types of small cells in LTE networks are subject of research on automated PCI assignment. The complexity of collision and confusion free assignment is in positive correlation with densification of deployed cells in a network. The previous chapter presents analysis and evaluation the probability of collision and confusion. It appoints several novel characteristics and indicators, which can be used to improve automated PCI allocation. It is diverse approach from the other authors, mentioned mostly in section 2.4 because it is based on extended analysis of confusion and collision issue. I reassume on the information about the essentials of femtocell deployment according to 3GPP, which was described in chapters 1.6.5 and 2.1, where some basics steps are defined to enable femtocells operation in a mobile network. Since I focus on LTE networks, therefore in 3GPP terminology I use the word HeNB in place of the femtocell term.

5.1 Centralized scheme

The first scheme assumes centralized approach to allocation, where a dedicated network entity self or a function residing in an existing entity is responsible for PCI allocation. Each HeNB has to send information about itself and other defined information prior to its operational state. These data can flow directly into HeNB gateway or, in other way of deployment, directly into CN entities such as MME and S-GW. I assume HeNB-GW is present in a network serving as HeNB concentrator. Upon registration, the HeNB Management System (HMS) is responsible for HeNB authentication and sending of correct setting. The logic for automated PCI assignment should reside in HMS and a new instance of automated PCI assignment function is triggered for each HeNB-GW in a network.

The first step is taken over from 3GPP to ensure compatibility with current networks. It comprises basic authentication, which has to be done for possibility of assignment of the high-level identities. These are mainly ECGI and CSG Identity. After basic communication with a CN via secured connection is established, the acquisition of PCI can be started. The proposed scheme can be defined in the following steps:

1) Establish communication with a HeNB according to 3GPP
2) Evaluate the probability of collision and confusion based on observable information
3) Analyse situation in term of clusters
4) Enforce optional constraints
5) Send response to the HeNB with valid PCI
6) Monitor and optionally retrigger from step 2

The second step exploits my evaluations crosschecked with calculations, which were created specifically for LTE with 504 PCIs. The several information can be used in the proposed scheme. On the presumption of HeNB-GW presence acting as aggregator of connections from HeNBs under limited area, the count of unique connections (HeNB identities) could serve to estimate the probability of collision and confusion. Aggregation on the HeNB-GW level is considered as the abstraction of the macrocell area. The curves from graphs on Figure 4.1 and Figure 4.2 show three different safety margins to estimate probability of collision and confusion based on chosen safety margin, SFM, (0, 20, or 100 m). Evaluation of the probability of confusion and collision based on the number of femtocell in an area assumes usage of the RANDM for rural areas or the DUM for urban locations. Limit for self-healing, L_{SH}, and SFM are two input parameters, which influence this evaluation phase and are dependent on capability of applied self-healing mechanisms and required QoS. These values can be adjusted according to used correction mechanisms in a HeNB and specific conditions in concrete network. A flag, $F_{ALGORITHM}$, determining, whether the random assignment is appropriate method or indicating various PCI assignment algorithms, based on the collision and confusion probability level, is output of this step. $F_{ALGORITHM}$ can take different values based the probability levels of p_{COL} and p_{CONF}. Thus, it can serve as efficient mechanism to switch between several sub-optimal solutions.

If the central entity will use random method to PCI assignment, it can evaluate overall probability of PCI misconfiguration under a HeNB-GW by simple Markov chain as depicted on the Figure 5.1.

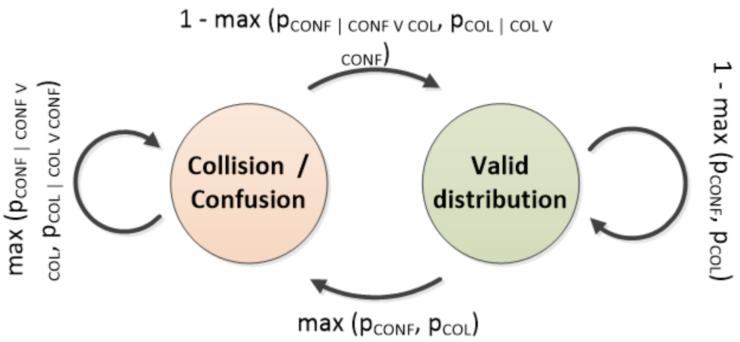

Figure 5.1 Markov chain for modelling state of PCI allocation by random method.

The model on Figure 5.1 signalize whether there is collision or confusion state for any HeNB under a HeNB-GW. If improper state is detected, it may request additional information from HeNBs to solve it. Thus, the central entity tries minimizing communication with femtocells and information acquisition only to intervals with probable collision and confusion state. The transition probabilities for the chain have to be set according to results stated in the section 4.1. The weights have to be updated as the number of HeNBs grows. This model also considers that all requests belonging to the same HeNB-GW will be processed in queue and not parallelised. The parallel processing is only possible for request belonging for different HeNB-GWs.

The third step consists of estimation of required PCI range, PCI_{RANGE}, for assignment based on clusters. The N_{HeNBs} can be used to estimation of maximal number of neighbours both at one-hop and two-hop level, $N_{NBmax(L1/L2)}$. The sum of these numbers forms an upper bound of required PCI range. E.g. if at first-level there is maximum of 17 neighbours, and at second level 22 (see the Figure 4.24) then there is total of 39 + 1 PCIs needed to create valid distribution in the worst-case scenario. Moreover, minimum number of neighbours, $N_{NBmin(L1/L2)}$, together with $N_{NBmax(L1/L2)}$ can be used to optimize size of neighbour-list via variable $IniSize_{NL}$.

Since it is possible to estimate the number of clusters from the number of HeNBs in an area, the threshold value N_{FAPs}^{Tresh} , which indicates when no more clusters emerge in a network and when small clusters begin to join to bigger ones, can be derived. The threshold is important point, which implicates that until it the PCI allocation problem is divided into several independent clusters. The obtained value of N_{FAPs}^{Tresh} can be used to adjust $F_{ALGORITHM}$ because if $N_{HeNBs} > N_{FAPs}^{Tresh}$ the situation will need sophisticated solution.

The size of the biggest cluster of HeNBs determines the maximal number of required PCIs (see the Figure 4.21). Allocation of PCI should be done so that each of clusters should use the values from the same PCI set because after crossing the threshold N_{FAPs}^{Tresh}, the HeNBs, which cause that clusters start to merge (boundary HeNBs), can be assigned with values out of this

PCI range. It ensures that valid PCI distribution in particular cluster will not be corrupted and only the newly emerged HeNB on the boundary will be assigned with the new PCI value. This help prevents creation of loop of reconfigurations. If detailed map of adjacency of HeNBs, based on knowledge of position and neighbour-list, is available in a network then graph density can be used to appoint ratio of interconnection.

The fourth step involves optional point, where operator can manage PCI allocation by additional constraints, $Cstr_i$, (e.g. enforce splitting of PCI range for eNB and HeNB, or prohibit certain values for special purposes). **The fifth step** is responsible for selection of the concrete value of PCI to allocation based on the $F_{ALGORITHM}$ and the PCI_{RANGE} obtained in previous steps. **The sixth step** happens after all requests to PCI allocation are satisfied. It is monitoring phase, which may be dedicated to a HeNB-GW itself. In such case a HeNB-GW notifies the central entity when then change is detected on the number of unique connections. After it, the process is retriggered from step 2. Whole scheme is depicted on the Figure 5.2. It visualizes abovementioned logic for automated PCI configuration by centralised manner.

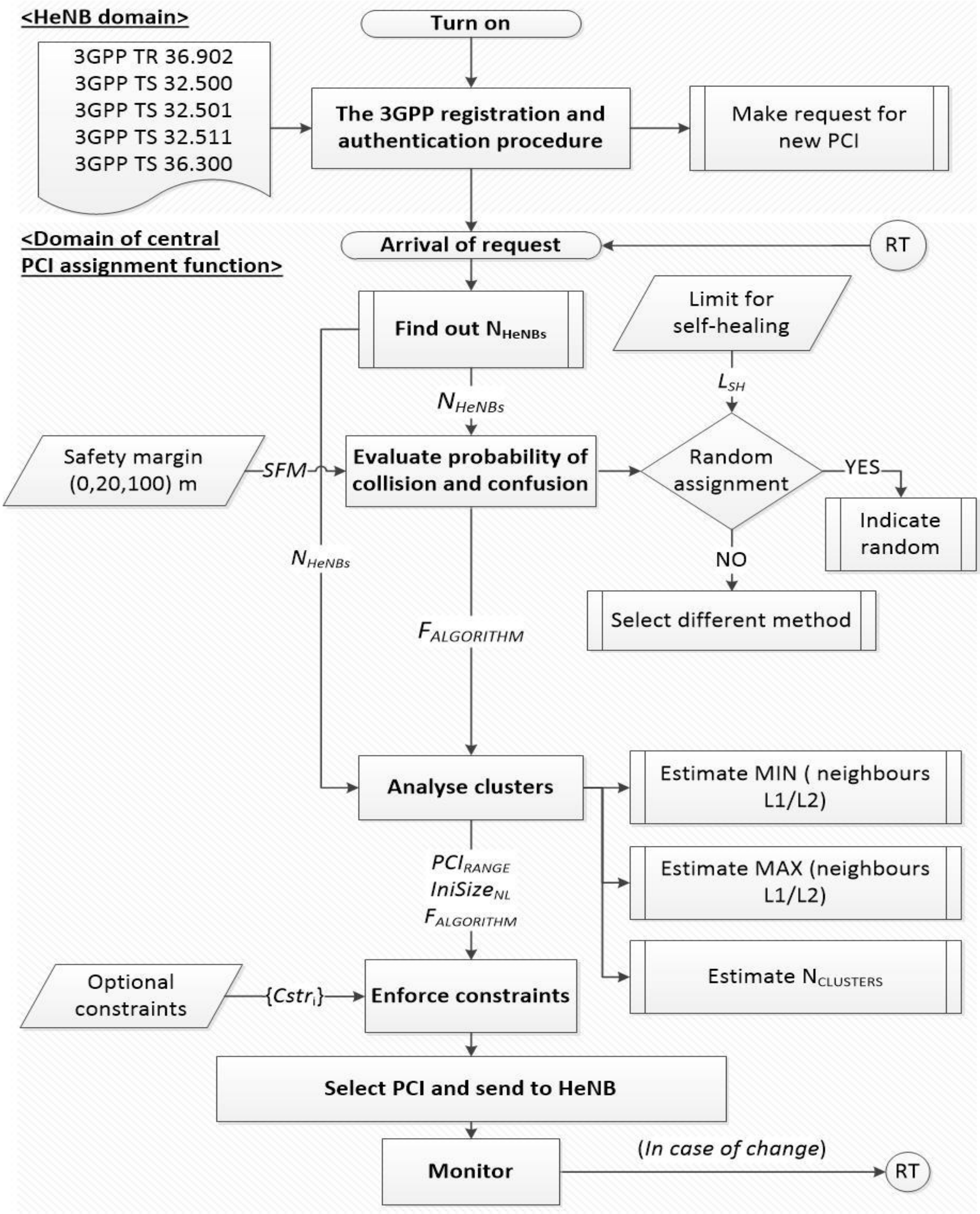

Figure 5.2 Proposed scheme to centralised PCI assignment.

The Figure 5.2 depicts scheme of centralized PCI assignment. It is aimed to minimize traffic overhead generated by HeNBs trying to use only the most relevant data and exploit evaluations referred in the chapter 4. The scheme is capable of satisfying both evolutionary growth scenario and initial setup phase, where certain number of HeNBs is deployed and all of them requests configuration at same time. It depends on capability of centralized function to handle multiple requests, but the scheme can be parallelised, as there is dependency only to the number of concentrated connections.

5.2 Distributed scheme

The distributed allocation scheme focuses to solve collision and confusion issue by means of a HeNB itself. Since cells in a mobile network have to cooperate and cannot conquer sources at expense of neighbouring cells, this scheme assume cooperative manner of distributed approach. However, for best achievable results, the mutual communication should be minimized to alleviate unnecessary overhead traffic. Basic procedures defined in the 3GPP standards have to be performed just like in the step 1 of the previous section 5.1. I suggest using the Nokia Siemens proposal on taking temporary PCI in initial phase of radio setting to obtain neighbour-list and enabling inter-cell communication to gather initial vector of data about surrounding environment. The steps of the distributed scheme are nearly identical with that in centralized approach, but different actions and indicators are proposed to utilize in particular sub steps. The scheme can be characterized as:

1) Establish communication with a core network according to 3GPP
2) Analyse of surrounding environment and cluster evaluation
3) Estimate probability of collision and confusion
4) Enforce optional constraints
5) Send response to request with valid PCI
6) Monitor and optionally retrigger from step 2

In the second step, the information from evaluation of clusters (see the section 4.5) of my thesis can be utilized. After successful registration of a HeNB, detection of neighbours has to be performed. It can be in passive mode at the first level (radio scanning) and simple message exchange with the number of cells in the neighbour-list from all of direct neighbours via X2 interface at the second level. There is no need to send all neighbour-list, because it burdens the bandwidth with unnecessary data. The key information is only the number of neighbours. This savings are important mainly in dense networks, where each unnecessary transferred bytes are multiplied with overall number of cells. The number of one-hop and two-hop neighbours, $N_{HeNBsL1/\mathrm{L2}}$, is known after detection of neighbours and therefore the IDR of max degree in clusters, IDR_{MaxDeg}, and IDR of size of clusters, IDR_{SCLUST}, can be estimated. I suggest considering the detected number of neighbours as the most frequent value, $N_{NB(L1/L2)}$, and then derive the number of HeNBs deployed in an area using appropriate model. Such assumption introduces a safety margin, because radio scanning has not to discover all possible neighbours. The estimated value of the number of HeNBs enables to obtain maximal, $N_{NBmax(L1/L2)}$, and minimal number, $N_{NBmin(L1/L2)}$, of neighbours. Both values can be considered as boundary inside which a solution of PCI should be found. The IDR_{SCLUST} (see the Figure 4.22), and IDR_{MaxDeg} (see the Figure 4.23) then reflects how clusters differs among themselves. In case the both values are sufficiently small, it signalize that middle 80 % of clusters have the same scenario and solution can be learned from other cells, because they solve similar problem before. In this case, the X2 communication can be used to optimize neighbour-list, *IniSizeNL*, and maximal number of used PCI, PCI_{RANGE}.

The third step consists in estimation of the probability bounds based on the $N_{HeNBsL1/\mathrm{L2}}$ obtained in the previous phase. There the probability of collision and confusion is evaluated according to selected model and input parameter *SFM*. The bigger value is taken in account. Output signalize whether random assignment provides sufficiently small probability of misconfiguration. The boundary whether or not it is sufficiently small has to be judged by additional input parameter L_{SH}, which determines the value based on used self-healing mechanism.

Output of this step is a flag, $F_{ALGORITHM}$, about used algorithm. Additionally probability of intersection can be incorporated into scheme to affect probability that neighbouring cells will be at distance and can provide local information. The equation stated in the Figure 4.5 can be used to estimate probability of intersection based on area computed only as product of the number of HeNBs and estimated area of a single HeNB.

The fourth step is optional and may introduce constraints, via set of $Cstr_i$, to HeNB selection scheme. These constraints should be obtained during initial registration with CN and should be similar to the referred ones in the previous sub section. **The fifth step** takes outcomes of the previous steps and chooses valid PCI based on them. If the $F_{ALGORITHM}$ indicates, random assignment then random generator chooses PCI, which is used to replace temporary PCI. In this time, the HeNB become operational, but sensing mechanism enabling self-healing is necessary to employ. Generally, the PCI selection algorithm can be switched from predefined family of various algorithms, some of them mentioned in chapter 2.4. The switching process can be controlled by different values of these indicators. **The sixth step** consists of sensing and monitoring of surrounding environment. In case of collision/confusion detection, the HeNB has to begin the process of reconfiguration. Additionally, a HeNB should prepare data needed to help with solution to the other HeNBs. Since the reconfiguration process is not managed centrally, the timer with random value can be triggered. After this period is out, the HeNB should use X2 to announce start of reconfiguration. The first come the first served should be applied, as simultaneous reconfigurations are not desirable in local area. The Figure 5.3 depicts the distributed scheme for automated PCI assignment.

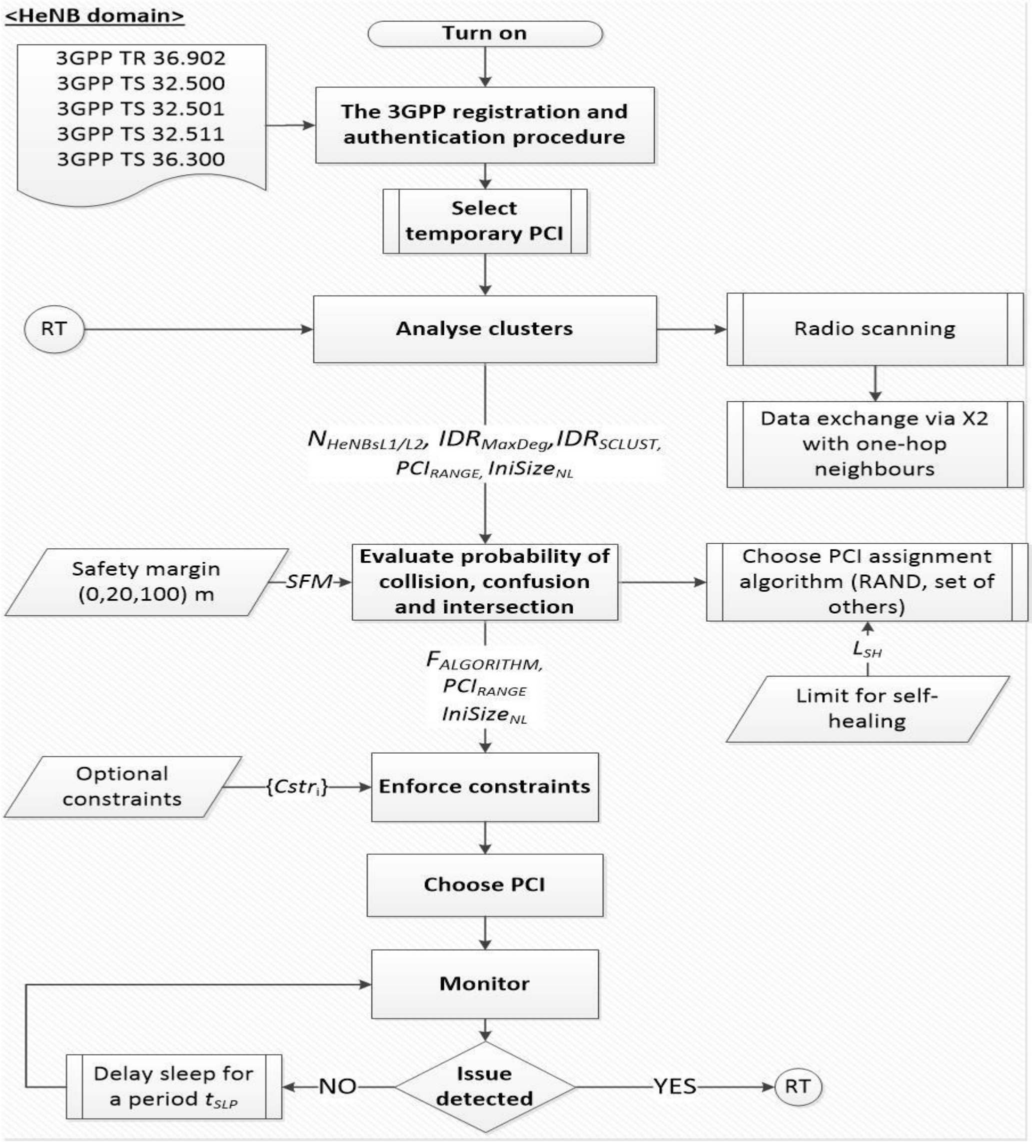

Figure 5.3 Proposed scheme to distributed PCI assignment.

There is one limitation to the distributed scheme and it is cost of such solution in a HeNBs. Since HeNBs should massively deployed and one presumption for this is price as low as possible, the distributed scheme should be implement with these regards.

5.3 Discussion

This chapter is built upon chapter 4, where I simulate and evaluate different femtocell scenarios. The results are used to lay out two different schemes of automated PCI assignment to HeNBs. The first scheme is based on centralized approach which provide greater flexibility in implementation compared to second scheme, the distributed approach, as there is only one or limited number of points where the PCI assignment function is triggered from. The distributed approach presents better scheme in term of less overhead generated toward the CN. Both schemes are defined deliberately more loosely in some steps. Thus, it can be considered as a framework, which can incorporate other algorithms, some of them were mentioned in chapter 2.4 and use proposed indicators to effectively scale and switch between several sub-optimal solutions. This thesis does not replace the other solutions but try incorporating all solutions into a common platform. In design of this framework, I try to reduce overhead traffic and use only minimum of information, but if bandwidth enables increased overhead traffic, some other data can be incorporated into schemes.

6 Contribution of thesis

I analysed importance of the Physical Cell Identity (PCI) in LTE networks and studied collision and confusion issue, which is connected with automated PCI assignment, then I proposed two models for purposes of evaluation different femtocell deployment inside a macrocell. The goal was to simulate dense femtocell deployment, which is desirable in 5G networks. In the next step, I conducted evaluation with different parameters and proposed indicators helping solve automated PCI assignment. In the last part, I used my findings to appoint two novel frameworks for automated PCI allocation in femtocell networks. Thus, the analysis and proposal of the framework for PCI selection is main contribution of my thesis. Main distinction of my thesis from previous researches rests in prior analysis of collision and confusion issue aimed to dense networks with femtocells. Such analysis is not mentioned anywhere else, and many of papers only aim to mathematical solution and do not deal with whole process of PCI assignment much deeper. It brings different overview on the problems of automated PCI assignment in femtocells networks. It shows that not in all cases, there is need to employ sophisticated methods, and shows under which conditions the probability of collision or confusion is negligible.

The other outcome ensue from it and it enable finer adjust of automated PCI allocation mechanism for concrete scenarios and deployment. It could be used as a guide to help refine PCI assignment process. Moreover, it can be accompanied with algorithms mentioned in related works with which in not mutually exclusive and results of this thesis can be used as signalization of that there is need of different PCI assignment solution. The future of mobile networks probably lays in Software Defined Mobile Networking and switch of particular solutions will be much easier there. Therefore, it is important to have an indicator showing the right direction and the proposed schemes may fulfil such function. They may be used as a traffic light and at the same time as a switch for purposes of automated PCI assignment. This brings flexibility and dynamic in applied solutions.

7 Conclusion

Small cells and femtocells as one of their sub-category are perspective technology not only for present mobile technology as 4G/LTE, but also to 5G networks, where deployment of dense and ultra-dense networks is highly anticipated. My thesis deals with identification of femtocells at physical level. There exists only limited set of identities. Since these identities are connected with physical layer, they have to be allocated according certain rules to prevent collision and confusion issue, which may cause service outage in an area. Even though, this dissertation study identification of femtocells in 4G/LTE networks, it is possible to make abstraction towards proposed dense networks in 5G networks.

In the regard of marked goals, I have fulfilled all the points. The collision and confusion issue was analysed in the chapter 2, where the background and research on this topic is referred together with limits of particular proposals. The collision and confusion issue was transformed to the problem of circle intersection, because mutual interactions are more important prior to exact model of propagation. As it turns out from the related works, a solution of automated PCI assignment is not easy task for femtocells and even for eNBs. Nevertheless, femtocells pose bigger challenge because of their uncoordinated deployment. Most of the proposals is aimed to solve it using graph theory, but does not consider broader concept of such solutions.

In the chapter 3, there proposed two different models to simulate dense deployment of femtocells and to obtain characteristics and indicators, which can be used in resolving of automated PCI assignment. They are called the Random and the Dense Urban model. These models deploy specific number of femtocells under different conditions inside a macrocell. They enable to study aforementioned issues. Additionally they can be further evolved or upgraded to different technology, as main points are easily to replace for different ones. These points are neighbouring function and set of limited resource, which is needed to configure in a network. The limited resource is the Physical Cell Identity in my thesis, because I assume mainly LTE network and neighbouring function is defined differently for each model as stated in sections 3.3 and 3.4.

The chapter 4 shows results from performed simulations on defined models. The probability characteristics are evaluated and various characteristics of clusters in the RANDM models are stated. It contains evaluation of the probability of collision, confusion for both models. Moreover, it also includes the probability of intersection and the cumulative distribution functions for number of neighbours and the probability function for number of neighbouring

FAPs. From the results can be concluded that except the situation in RANDM with offset 100 m that values of probability collision are insignificant on condition 504 different Physical Cell Identities. The confusion issue threaten automated PCI assignment more, because there is higher probability of confusion under assumption of random allocation. There is also possible to nearly 100 % chance of achieving confusion state in some scenarios and main component of the probability of confusion is event when newly emerged may be confused by other cells.

The presented results can be utilized to decide which cell identity assignment methods should be applied in the given situation. This means, for small number of FAPs in the macrocell a newly emerged FAP can randomly chose any physical identity without investigating and checking the neighbouring cells and their identities. This speeds up the FAP initialization time and reduces HW requirements. In later stage, as the number of FAPs increased (and thus the probability of intersection and the probability of collision), a newly introduced FAP can activate, for example the scanning mechanism to firstly check identifiers of neighbouring FAPs to avoid using the same cell identifier or engage sophisticated mechanism, e.g. those described in section. The cluster section 4.5 describes and proposes some indicators as the IDR of number of clusters, the IDR of maximal degree, minimal and maximal number of neighbours to affect the fact the femtocells tend to create clusters. These specific features can be utilized to design automated PCI configuration.

As it can be seen further, the RANDM is comparable to the DUM on the assumption that determination of adjacency is based on the distance and the street width lays in range from five to ten meters is used. If the street is wider, the probability of collision in the DUM, against expectations, is increasing. The reason is the denser grid. Based on outputs from evaluating the DUM with neighbour list adjacency, it may be observed that the resulting probability of collision is lower than in DUM with distance-based neighbourhood. Even the RANDM may be considered for evaluating probability of collision in urban areas but results will be slightly higher than if the DUM would be used with neighbour list method for adjacency appointment. This increase but could be viewed as safety margin, but advantage of RANDM before DUM is its simpler implementation. Beyond that, by introduction offset in determination of neighbourhood to the RANDM it is possible to affect randomness of position of a femtocell.

I deal with proposal on a framework for automated PCI assignment in the chapter 5. There I utilized results obtained from the evaluation of the RANDM and the DUM to lay out scheme for PCI assignment. As allocation can be done by centralized approach and distributed approach and both cases have both cons and pros, I decided to design scheme for both approaches. The centralized scheme is easily manageable because it contains only one controlling point, which can be flexibly changed, but distributed scheme offers advantage of less overhead traffic as each femtocell is considered standalone during automated PCI assignment.

In sum, this thesis introduces extensive analysis of identification, evaluation, and proposal of the framework for automated PCI assignment with two different approaches created specifically for femtocells.

7.1 Future work

In the future, this work can be extended about some real world scenarios e.g. a model for some large European city, where performance characteristics under example deployment would be evaluated and concrete values for particular indicators would be appointed. As the exact value of the indicators is dependent to used technology, such evaluation has to be done with standardised specifications.

If the values of the indicators would be known from the research outlined in the previous paragraph then it could be used to make complete simulation of automated process of PCI assignment with several algorithms mentioned in the chapter 2.4 and evaluate overall performance when the sub-optimal solutions are switched. However, this is impossible before accomplishment of the mentioned research. The exact values are interesting point but it was not aim of my thesis since I try to do certain level of abstraction and without it was impossible to move into next phases outlined here.

The proposed models also have limitation that they lay only in 2D space so they can be expanded into three-dimensional space. It can bring additional findings mainly in dense agglomeration with high buildings. The neighbourhood function has to be replaced for such models.

List of Abbreviations

3GPP	The Third Generation Partnership Project
ABT	Asynchronous Backtracking
AMPS	Advanced Mobile Phone System
AMR	Adaptive Multi-Rate Wide-Band
ANR	Automatic Neighbour Relation
API	Application Programming Interface
ARPU	Average Revenue per User
AWC	Asynchronous Weak-Commitment
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CI	Cell Identity
CN	Core network
CPE	Customer Premises Equipment
CPU	Central Processing Unit
CRE	Cell Range Extension
CS	Circuit Switched
CSG	Closed Subscribers Group
CWMP	CPE Wide Area Network Management Protocol
DAS	Distributed Antenna Systems
DBO	Distributed Breakout
DLC	Digital Loop Carrier
DoS	Denial of Service
DR	Delay Registration
DSA	Distributed Stochastic Algorithms
DSLAM	Digital Subscriber Line Access Multiplexer
DUM	Dense Urban model
ECGI	E-UTRAN Cell Global Identifier
EDGE	Enhanced Data Rates for Global Evolution
EPC	Evolved Packet Core
EPS	Evolved Packet System

E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FAP	Femto Access Point
FMC	Fixed Mobile Convergence
GATO	Global Access Traffic Offload
GD	Graph density
GERAN	GSM EDGE Radio Access Network
GHBS	GSM Home Base-Stations
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSO	Glow-worm Swarm Optimization
HMS	HeNB Management System
HSCD	High-Speed Circuit Switched Data
HSPA	High Speed Packet Access
HSS	Home Subscriber Server
IDC	In-Device Co-Existence
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMS	IP Multimedia Subsystem
IMT	International Mobile Telecommunication
IoT	Internet of things
ITU	International Telecommunication Union
LAN	Local Area Network
LATO	Local Access Traffic Offload
LBS	Location-based services
LIPA	Local IP Access
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MNO	Mobile Network Operator
MST	Minimum Spanning Tree
MTC	Machine Type Communication

NGMNA	Next Generation Mobile Network Alliance
NMT	Nordic Mobile Telephony
OPEX	Operational expenditures
PCI	Physical Cell Identity
PCRF	Policy and Charging Function
PLMN	Public Land Mobile Network
PON	Passive Optical Networks
QoS	Quality of services
RACH	Random Access Channel
RAN	Radio Access Network
RANDM	Random model
RAT	Radio Access Technologies
RIPA	Remote IP Access
RN	Relay Node
RRC	Radio Resource Configuration
RRH	Remote Radio Head
RSS	Received Signal Strength
SAE	System Architecture Evolution
SCF	Small Cells Forum
SDMN	Software-Defined Mobile Networking
SDO	Standard Development Organizations
SFN	System Frame Number
SGSN	Serving GPRS Support Node
SIPTO	Selected IP Traffic Offload
SON	Self-Organized Network
UE	User Equipment
UMB	Ultra Mobile Broadband
UMTS	Universal Mobile Telecommunication System
UTRAN	Universal Terrestrial Radio Access Network
VNF	Virtualize Networks Functions
WA	Wi-Fi Alliance

Publications of Author

A. Journals with impact factor

SEDLACEK, Marek; and BESTAK, Robert. Analysis of Neighbourhood Relations for Femtocell Networks. *Wireless Personal Communications*, 2016, pp. 1-14. ISSN 1572-834X.

SEDLACEK, Marek; and BESTAK, Robert. Evaluation of Random Physical Cell ID assignment to femtocells under dense cell deployments. *Computers & Electrical Engineering.* ISSN: 0045-7906 (in review process)

B. International Conferences

BESTAK, R. and M. SEDLACEK. Overlapping Cells in Femtocell Environment. *In: 6th Joint IFIP Wireless and Mobile Networking Conference (WMNC).* Wireless and Mobile Networking Conference, Dubai, 2013-04-23/2013-04-25. Dubai: The Canadian University of Dubai, 2013. p. 1-5. ISBN 978-1-4673-5614-5. DOI 10.1109/WMNC.2013.654901

SEDLACEK, M. and R. BESTAK. Probability of Cell Overlapping in Femtocell Environment. In: *HERENCSÁR, N. a K. MOLNÁR, eds. 36th International Conference on Telecommunications and Signal Processing. 36th International Conference on* Telecommunications and Signal Processing, Rome, 2013-07-02/2013-07-04. Piscataway: IEEE, 2013. p. 244-248. ISSN 1805-5435. ISBN 978-1-4799-0404-4. DOI 10.1109/TSP.2013.6613929

SEDLACEK, Marek; and BESTAK, Robert. Proposal on automated PCI assignment framework for femtocells in LTE networks. In *Mechatronics, 2017 12th International Conference.* Brno, 2017 (in review process)

SEDLACEK, M. a R. BESTAK. Deployment of Femtocells. In: KRIVANEK, V. and A. STEFEK, eds. ICMT'13 - *Proceedings of the International Conference on Military Technologies*. International Conference on Military Technologies, Brno, 2013-05-22/2013-05-23. Brno: Univerzita obrany, 2013. p. 547-552. ISBN 978-80-7231-917-6

Bibliography

[1] AL AGHA, Khaldoun, PUJOLLE, Guy and YAHIHA, Tara. *Mobile and Wireless Networks*. 1st ed. US: Iste, 2015. ISBN 1848217145.

[2] 3GPP. *3GPP Releases*. Available from:<http://www.3gpp.org/specifications/releases>.

[3] 3GPP. *3GPP TS 23.228, IP Multimedia Subsystem (IMS); Stage 2, Rel.12,* Mar, 2014.

[4] LIN, Ling; and LIOTTA, Antonio. Presence in the IP Multimedia Subsystem. *Mobile Information Systems*, 2007, vol. 3, 3.3-4: 187-202.

[5] 3GPP. *Overview of 3GPP Release 8 V0.3.3*. Sept, 2014.

[6] QIU, Pei-Chen; CHEN, Whai-En; JIANG, Jehn-Ruey. Traffic Offloading with Mobility in LTE HeNB Networks. In: *Parallel and Distributed Systems (ICPADS), 2015 IEEE 21st International Conference on*. IEEE, 2015. p. 809-814.

[7] FIRMIN, Fréderic. *The Evolved Packet Core*. Available from: <http://www.3gpp.org/technologies/keywords-acronyms/100-the-evolved-packet-core>.

[8] GSM Alliance. *VoLTE Service Description and Implementation Guidelines*. , Mar 26, 2014.

[9] 3GPP. *3GPP TS 23.272 V13.4.0, Circuit Switched (CS) Fallback in Evolved Packet System (EPS).* Jun, 2016.

[10] GSM Alliance. *VoWifi*. Available from: <http://www.gsma.com/network2020/technology/vowifi/>.

[11] ITU. *ITU Global Standard for International Mobile Telecommunications ´IMT-Advanced´*. Jan 20, 2012Available from: <http://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-adv/Pages/default.aspx>.

[12] ITU-R. *REPORT ITU-R M.2134: Requirements Related to Technical Performance for IMT-Advanced Radio Interface(s) ITU,* Dec 11, 2008.

[13] 3GPP. *LTE-Advanced Pro Ready to Go.* Oct 28, 2015. Available from: <http://www.3gpp.org/news-events/3gpp-news/1745-lte-advanced_pro>.

[14] YUAN, Hu; GUO, Weisi; WANG, Siyi. Device-to-Device communications in LTE-Unlicensed heterogeneous network. In: *Signal Processing Advances in Wireless Communications (SPAWC), 2016 IEEE 17th International Workshop on*. IEEE, 2016. p. 1-5.

[15] SEYBOLD, Andrew. *The End of the Road for WiMAX*. Oct 23, 2014. Available from:<http://andrewseybold.com/3486-the-end-of-the-road-for-wimax>.

[16] GSMA Intelligence. *Global Mobile Trends.* Oct, 2016. Available from: <https://www.gsmaintelligence.com/research/?file=357f1541c77358e61787fac35259dc92&download>

[17] TALEB, Tarik; BAGAA, Miloud; KSENTINI, Adlen. User mobility-aware virtual network function placement for virtual 5G network infrastructure. In: *Communications (ICC), 2015 IEEE International Conference on*. IEEE, 2015. p. 3879-3884.

[18] ZAIDI, Slim, et al. Wireless Access Virtualization Strategies for Future User-Centric 5G Networks. In*: Globecom Workshops (GC Wkshps), 2016 IEEE*. IEEE, 2016. p. 1-7.

[19] ROST, Peter, et al. Mobile network architecture evolution toward 5G. *IEEE Communications Magazine*, 2016, 54.5: 84-91.

[20] 3GPP. *SA1 Completes its Study into 5G Requirements*. Jun 23, 2016. Available from:<http://www.3gpp.org/news-events/3gpp-news/1786-5g_reqs_sa1>.

[21] KINNEY, Sean. *What is IMT-2020 and what does it Mean for 5G?* Mar 27, 2016. Available from:<http://www.rcrwireless.com/20160307/policy/what-is-imt-2020-tag17-tag99>

[22] GALINDO-SERRANO, Ana, et al. Virtual small cells using large antenna arrays as an alternative to classical HetNets. In: *Vehicular Technology Conference (VTC Spring), 2015 IEEE 81st*. IEEE, 2015. p. 1-6.

[23] ITU. *ITU Towards IMT for 2020 and Beyond*. Available from: <http://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx>.

[24] 3GPP. *About 3GPP*. Available from: <http://www.3gpp.org/about-3gpp/about-3gpp>.

[25] 3GPP. *3GPP TS 23.139, Fixed Broadband Access Network Interworking*; V12.3.Mar, 2016.

[26] Broadband Forum. *TR-291, Nodal Requirements for Interworking between Next Generation Fixed and 3GPP Wireless Access*. Mar, 2014.

[27] LEITÃO, Filipe; ROS, Roberto David Carnero; I RIU, Jãume Rius. Fixed-mobile convergence towards the 5G era: Convergence 2.0: The past, present and future of FMC standardization. In: *Standards for Communications and Networking (CSCN), 2016 IEEE Conference on*. IEEE, 2016. p. 1-6.

[28] ALI, Mohamed A., et al. On the vision of complete fixed-mobile convergence. *Journal of Lightwave Technology*, 2010, 28.16: 2343-2357.

[29] Qualcomm. A Comparison of LTE Advanced HetNets and Wi-Fi. , Oct, 2011.

[30] WANNSTROM, Jeanette. *HetNet/Small Cells*. Available from: <http://www.3gpp.org/hetnet>.

[31] STANZE, Oliver; and WEBER, Andreas. Heterogeneous Networks with LTE-Advanced Technologies. *Bell Labs Technical Journal*, 2013, vol. 18, no. 1, pp. 41-58. ISSN 1538-7305.

[32] WANNSTROM, Jeanette. *LTE-Advanced*. Jun, 2013. Available from:<http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced>.

[33] UMTS Forum. *3G/4G Subscriptions Pass 3 Billion Milestone*. May, 2015. Available from: <http://www.umts-forum.org/content/view/4655/303/>.

[34] GSMA. *Understanding the Internet of Things (IoT).* GSMA, Jul, 2014.

[35] Small Cells Forum. *Small Cells: Elevator Pitch*. Small Cells Forum. Available from: <http://www.smallcellforum.org/about/about-small-cells/elevator-pitch/>.

[36] KEMP, Simon. *Digital in 2016*. We Are Social, Jan 26, 2016. Available from: <http://wearesocial.com/uk/special-reports/digital-in-2016>.

[37] UMTS Forum. *Mobile traffic forecasts 2010-2020 report, Report 44*. UMTS Forum, Jan, 2011.

[38] Cisco. *Cisco Visual Networking Index: Global Mobile: Data Traffic Forecast Update, 2015–2020*. Feb 3, 2016.

[39] Networks Strategies. *LTE Vs ARPU – Data Takes Over*. Dec 1, 2013. Available from: <http://www.strategies.nzl.com/wpapers/2013014.htm>.

[40] Ericsson. *Optimizing the Indoor Experience*. Ericsson, 2013.

[41] Cisco. *Indoor Small Cells:A Guide to Mission-Critical Communication*.

[42] Cisco. *Cisco Visual Networking Index: Global Mobile DataTraffic Forecast Update, 2010–2015*, Feb 1, 2011.

[43] Amdocs. *Amdocs Network Research: VoLTE Call Drops are 4-5 Times Higher than 2G/3G Calls*. Feb 4, 2016. Available from: <http://www.amdocs.com/news/pages/amdocs-network-research-volte-call-drops.aspx>.

[44] LILIEHOLM, Erik. *CommScope Definitions: What is Network Densification?* Dec 11, 2015. Available from: <http://www.commscope.com/Blog/CommScope-Definitions-What-Is-Network-Densification/>.

[45] ZHANG, Haijun, et al. Fronthauling for 5G LTE-U ultra dense cloud small cell networks. *IEEE Wireless Communications*, 2016, 23.6: 48-53.

[46] HENZE, Thomas. *eSIM: An Opportunity for Operators to Innovate*. Apr 27, 2016. Available from: <http://www.gsma.com/rsp/2016/04/27/esim-opportunity-operators-innovate/>.

[47] IHS Technology. *Small Cell Strategies and Vendor Leadership*. IHS Technology, Sep 19, 2016.

[48] 3GPP. *3GPP TS 23.401 V14.2.0, General Packet Radio Service (GPRS) Enhancements for Evolved Universal Terrestrial Radio Access Network (E-UTRAN) Access*. Dec, 2016.

[49] 3GPP. *3GPP TS 23.203 V14.2.0, Policy and Charging Control Architecture*. Dec, 2016.

[50] CHAMBERS, David. *Femtocell History*. Oct 19, 2008. Available from:<https://www.thinksmallcell.com/FAQs/femtocell-history.html>.

[51] SANCHEZ, Javier; THIOUNE, Mamadou. AMR Codec in UMTS. *UMTS*, 2010, 375-381.

[52] Small Cell Forum. *Femto Forum Becomes Small Cell Forum as Femtocell Technology Extends Beyond the Home*. Feb 15, 2012. Available from: <http://www.smallcellforum.org/press-releases/femto-forum-becomes-small-cell-forum-femtocell-technology-extends-beyond-home/>.

[53] Small Cells Forum. *About Small Cells*. Small Cells Forum. Available from: <http://www.smallcellforum.org/about/about-small-cells/small-cell-definition/>.

[54] KNISELY, D.; YOSHIZAWA, T.and FAVICHIA, F. 3GPP: Standardization of Femtocells. World Appl Program, 2011, pp. 47p.

[55] 3GPP. *3GPP TS 25.367 V9.4.0, Mobility Procedures for Home Node B (HNB)*. Jun, 2010.

[56] 3GPP. *3GPP TR 32.816, Study on Management of Evolved Universal Terrestrial Radio Access Network (E-UTRAN) and Evolved Packet Core (EPC)*. Dec, 2012.

[57] FENG, Sujuan; and SEIDEL, Eiko. Self-Organizing Networks (SON) in 3GPP Long Term Evolution. *Novel Mobile Radio Research*, 2008.

[58] TARIQ, Faisal, et al. A Cell Range Expansion Framework for Closed Access Femtocell Networks. *Wireless Personal Communications*, 2014, pp. 1-14.

[59] LPEZ-PREZ, David, et al. OFDMA Femtocells: A Roadmap on Interference Avoidance. *IEEE Communications Magazine*, 2009, vol. 47, no. 9.

[60] CLAUSSEN, Holger; HO, Lester T. W.and SAMUEL, Louis G. An Overview of the Femtocell Concept. *Bell Labs Technical Journal*, 2008, vol. 13, no. 1, pp. 221-245. ISSN 1538-7305.

[61] IRMER, Ralf, et al. Coordinated multipoint: Concepts, performance, and field trial results. *IEEE Communications Magazine*, 2011, 49.2: 102-111.

[62] ZHANG, Huanle; LIU, Jianand SHI, Haili. Analysis of Accessing to the Nearest and to the Strongest Base Station in Femtocell Networks. *International Journal of Communication Systems*, 2017, vol. 30, no. 1, pp. n/a. ISSN 1099-1131.

[63] HAN, Kwanghun, et al. Automatic neighboring BS list generation scheme for femtocell network. In: Ubiquitous and Future Networks (ICUFN), 2010 Second International Conference on. IEEE, 2010. p. 251-255.

[64] CHAMBERS, David. *Femtocell Security Over the Internet*. Sep 19, 2008. Available from:<https://www.thinksmallcell.com/Technology/femtocell-security-over-the-internet.html>.

[65] 3GPP. *3GPP TS 33.320 V14.0.0, Security of Home Node B (HNB) / Home Evolved Node B (HeNB).* Dec 17, 2016.

[66] SAEED, R. A. *Femtocell Communications and Technologies: Business Opportunities and Deployment Challenges: Business Opportunities and Deployment Challenges*. Information Science Reference, 2012. ISBN 9781466600935.

[67] 3GPP. *3GPP TS 22.220, Service Requirements for Home Node B (HNB) and Home eNode B (HeNB), V9.0.0*. Mar 24, 2009.

[68] KHAN, Muhammad Farhan; KHAN, Muhammad Imran; RAAHEMIFAR, Kaamran. Local IP Access (LIPA) enabled 3G and 4G femtocell architectures. In: *Electrical and Computer Engineering (CCECE), 2011 24th Canadian Conference on*. IEEE, 2011. p. 001049-001053.

[69] SEIDEL, Eiko; SAAD, Elie. LTE Home Node Bs and its enhancements in Release 9. *Nomor Research*, 2010, 1-5.

[70] SCARPATI, Jessica. *Small Cells, Partnerships Fuel Mobile Location-Based Services Market*. Feb 16, 2011. Available from: <http://searchtelecom.techtarget.com/news/2240032247/Small-cells-partnerships-fuel-mobile-location-based-services-market>.

[71] NEC. *Nec's Femtoell Services - Converged Multimedia Services for the Digital Home*. 2009. Available from:<http://www.nec.com/femto/>.

[72] GUBBINS, Ed. *Nokia Small Cells*. Jun 20, 2016.

[73] Small Cells Forum. *Femto Forum Addresses Apps Market with Femtocell API Specification and Evolved Management Standard*. Mar 22, 2011. Available

from:<http://www.smallcellforum.org/press-releases/femto-forum-addresses-apps-market-femtocell-api-specification-evolved-management-standard/>.

[74] Find Me 911 Coalition. *Psap Survey on Wireless 9-1-1 Location Accuracy*. Apr 24, 2014.

[75] BBF. *TR-069 CPE WAN Management Protocol, Amendment 5*. Nov, 2013.

[76] 3GPP. *3GPP TR 36.300 Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN)*, Mar, 2014.

[77] NGMN. *NGMN Technical Achievements 2007 – 2010*. Dec 16, 2010. Available from: <https://www.ngmn.org/uploads/media/NGMN_Technical_Achievements_2007-2010.pdf>.

[78] KIM, Junsik, et al. SON and femtocell technology for LTE-advanced system. In: Wireless and Mobile Communications (ICWMC), 2010 6th International Conference on. IEEE, 2010. p. 286-290.

[79] MEHTA, Mahima, et al. A Self-Organized Resource Allocation Scheme for Heterogeneous Macro-Femto Networks. *Wireless Communications and Mobile Computing*, 2016, vol. 16, no. 3, pp. 330-342. ISSN 1530-8677.

[80] 3GPP. *3GPP R3-081090, Automatic Physical Cell Identity Selection in LTE: Requirements and Solutions*. May, 2008.

[81] GOLAUP, Assen; MUSTAPHA, Mona; PATANAPONGPIBUL, Leo Boonchin. Femtocell access control strategy in UMTS and LTE. *IEEE Communications Magazine*, 2009, 47.9: 117-123.

[82] 3GPP. *3GPP TS 36.211 V14.1.0, E-UTRA Physical Channels and Modulation*. Dec, 2016.

[83] 3GPP. *3GPP TS 36.133 V 12.1.0, Requirements for Support of Radio Resource Management*. Sep 27, 2013.

[84] KANTOLA, Raimo. *Performance of Handover in Long Term Evolution*. 2011. PhD Thesis. Aalto University.

[85] 3GPP. *3GPP TR 36.902 V9.3.1 Self-Configuring and Self-Optimizing Network (SON) use Cases and Solutions*. Mar, 2011.

[86] PREMNATH, K. N., et al. Self-configuration of basic LTE radio parameters using Magnetic Field Model. In: *Wireless Communication Systems (ISWCS), 2012 International Symposium on*. IEEE, 2012. p. 36-40.

[87] 3GPP. *3GPP R3-080812 Solution(s) to the 36.902's Automated Configuration of Physical Cell Identity use Case*. Mar 3, 2008.

[88] ABDULLAH, Labeeb Mohsin; BABA, Mohd Daniand ALI, Sinan Ghassan Abid. Self-Configuration Concept to Solve Physical Cell Id Conflict for SON Lte-Based Femtocell Environment. *International Journal on Recent Trends in Engineering & Technology*, 2014, vol. 10, no. 2, pp. 165.

[89] BANDH, Tobias, et al. Optimized network configuration parameter assignment based on graph coloring. In*: Network operations and management symposium (NOMS), 2010 IEEE*. IEEE, 2010. p. 40-47.

[90] SHAHAB, Muhammad Basit; BHATTI, Abdul Aziz. Neural Networks Based Physical Cell Identity Assignment for Self Organized 3GPP Long Term Evolution. In:

Telecommunications and Signal Processing (TSP), 2012 35th International Conference on. IEEE, 2012. p. 173-177.

[91] ZHANG, Cheng-fu, et al. Self-Configuration of Physical Cell Identity in LTE Based on Improved GSO Algorithm. In: *Proceedings of 20th International Conference on Industrial Engineering and Engineering Management*. Springer Berlin Heidelberg, 2013. p. 377-387.

[92] YU, Jingjie; PENG, Mugen; LI, Yue. A physical cell identity self-organization algorithm in LTE-advanced systems. In: *Communications and Networking in China (CHINACOM), 2012 7th International ICST Conference on*. IEEE, 2012. p. 576-580.

[93] 3GPP. *3GPP R3-080376, SON use Case: Cell Phy ID Automated Configuration*. May, 2008.

[94] 3GPP. *3GPP R1-082747, Summary of Options to Extend the PCI Space*. Jul, 2008.

[95] KWON, Sungoh; LEE, Neung-Hyung. Virtual extension of cell IDs in a femtocell environment. In: W*ireless Communications and Networking Conference (WCNC), 2011 IEEE*. IEEE, 2011. p. 428-433..

[96] 3GPP. *3GPP R2-084563, New Solution for CSG-Cell Identification*. Aug, 2008.

[97] LIU, Yanguang, et al. Graph based automatic centralized PCI assignment in LTE. In: *Computers and Communications (ISCC), 2010 IEEE Symposium on*. IEEE, 2010. p. 919-921.

[98] BANDH, Tobias; CARLE, Georg; SANNECK, Henning. Graph coloring based physical-cell-ID assignment for LTE networks. In: *Proceedings of the 2009 international conference on wireless communications and mobile computing: Connecting the world wirelessly*. ACM, 2009. p. 116-120.

[99] ABDULLAH, Labeeb Mohsin; BABA, Mohd Dani; ALI, Sinan Ghassan Abid. A novel scheme to resolve PCI conflicts and assignment problems in LTE-femtocell networks. In: *System Engineering and Technology (ICSET), 2013 IEEE 3rd International Conference on*. IEEE, 2013. p. 109-112.

[100] WU, Yi, et al. Physical cell identity self-organization for home eNodeB deployment in LTE. In: *Wireless Communications Networking and Mobile Computing (WiCOM), 2010 6th International Conference on*. IEEE, 2010. p. 1-6.

[101] FU, Huai-Lei; LIN, Phone; LIN, Yi-Bing. Reducing signaling overhead for femtocell/macrocell networks. *IEEE Transactions on Mobile Computing*, 2013, 12.8: 1587-1597.

[102] WEI, Yao, et al. Automatic Distributing Schemes of Physical Cell Identity for Self-Organizing Networks. *International Journal of Distributed Sensor Networks*, 2012.

[103] AHMED, Furqan, et al. Distributed Graph Coloring for Self-Organization in LTE Networks. *Journal of Electrical and Computer Engineering*, 2010, vol. 2010, pp. 5.

[104] 3GPP. *3GPP R3-082228, Framework for Distributed PCI Selection*. Aug, 2008.

[105] FEWELL, M. P. *Area of common overlap of three circles*. DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION EDINBURGH (AUSTRALIA) MARITIME OPERATIONS DIV, 2006.

[106] LIBRINO, Federico; LEVORATO, Marcoand ZORZI, Michele. An Algorithmic Solution for Computing Circle Intersection Areas and its Applications to Wireless

Communications. *Wireless Communications and Mobile Computing*, 2014, vol. 14, no. 18, pp. 1672-1690.

[107] MATHAR, Rudolf; and NIESSEN, Thomas. Optimum Positioning of Base Stations for Cellular Radio Networks. *Wireless Networks*, 2000, vol. 6, no. 6, pp. 421-428.

[108] ZAIDI, Monji; TOURKI, Rached; OUNI, Ridha. A new geometric approach to mobile position in wireless LAN reducing complex computations. In: *Design and Technology of Integrated Systems in Nanoscale Era (DTIS), 2010 5th International Conference on*. IEEE, 2010. p. 1-7.

[109] NOURANI, Fatemeh; JAMALI, Mohammad Ali Jabrail. Improved Circles Intersection Algorithm for Localization in Wireless Sensor Networks. In: *Software Engineering Artificial Intelligence Networking and Parallel/Distributed Computing (SNPD), 2010 11th ACIS International Conference on*. IEEE, 2010. p. 129-133.

[110] SKIENA, S. *Breadth-First and Depth-First Search. Implementing Discrete Mathematics: Combinatorics and Graph Theory with Mathematica*, Reading, MA: Addison-Wesley, 1990, pp. 95-97.

[111] Wolfram Mathematica. *Graph Density*. Available from: <http://reference.wolfram.com/language/ref/GraphDensity.html>.

[112] WELSH, D. J. A.; and POWELL, M. B. An Upper Bound for the Chromatic Number of a Graph and its Application to Timetabling Problems. *The Computer Journal*, 1967, vol. 10, no. 1, pp. 85.

[113] Qualcomm Research, "*Neighborhood Small Cells for HyperDense Deployments: Taking HetNets to the Next Level*", Feb 8., 2013. Available from <https://www.qualcomm.com/media/documents/files/qualcomm-research-neighborhood-small-cell-deployment-model.pdf.>

Annex A Percent occurrence of number of neighbours in RANDM

There are showed additional characteristics of the number of neighbours for newly introduced femtocell among N other FAPs in the RANDM, where offset distances in appointment of adjacency were changed to different values. The x-axis represents the number of neighbours and the y-axis is relative frequency of number of neighbours obtained during simulations. The parameters of particular scenarios are listed in the figures.

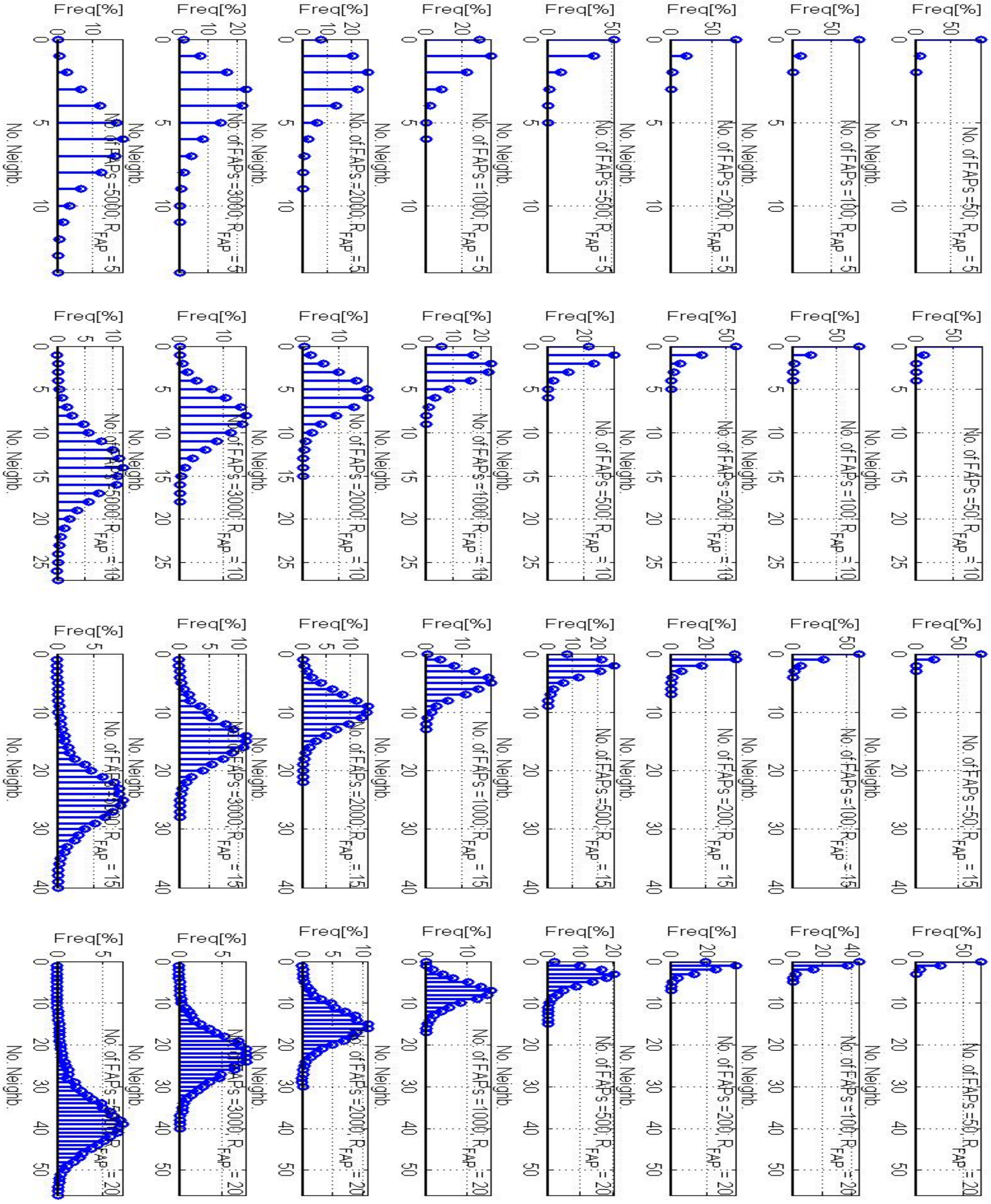

Figure A. 1 RANDM – Percent occurrence of N_{NEIGHB}, offset distance 10 m.

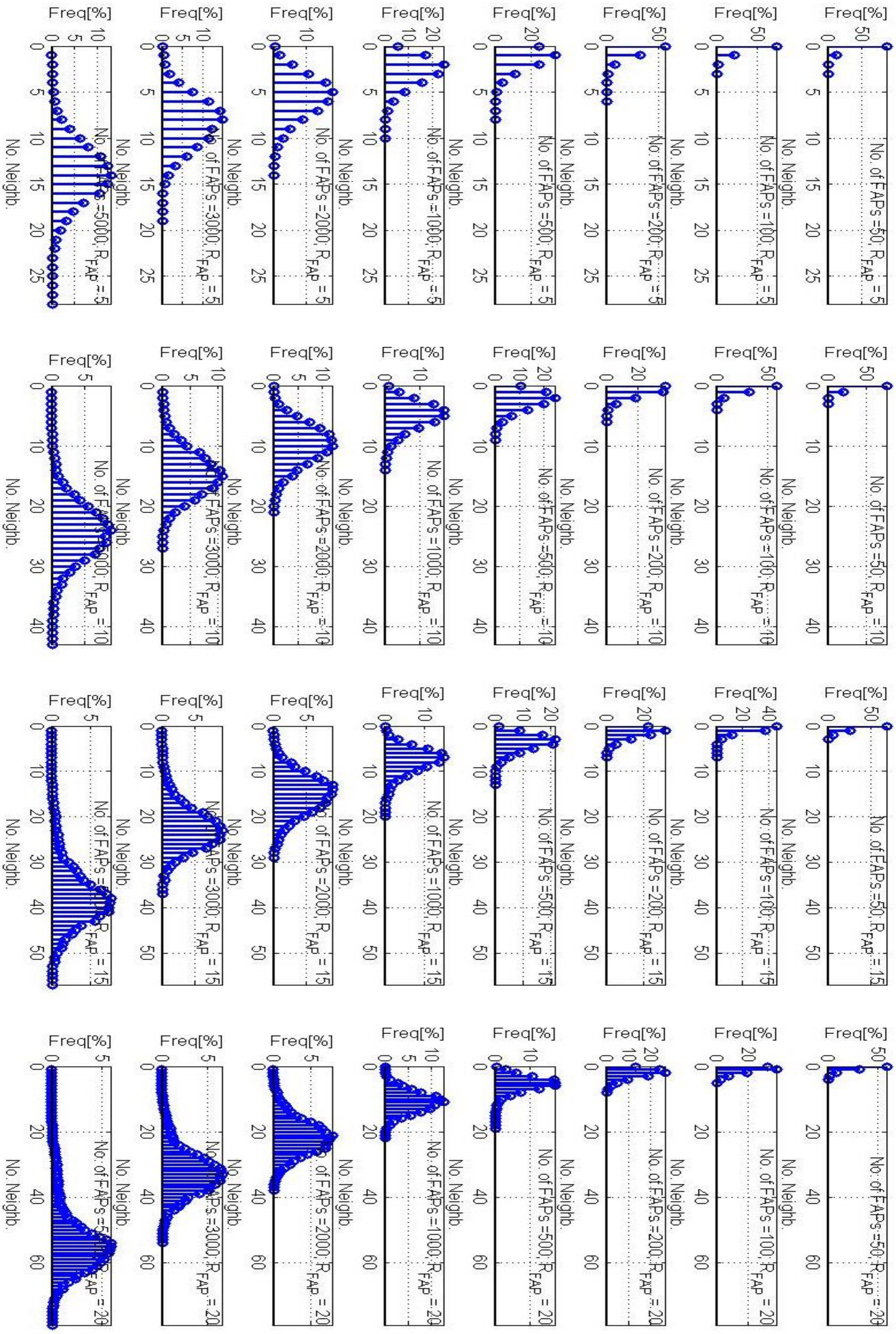

Figure A. 2 RANDM – Percent occurrence of N_{NEIGHB}, offset distance 20 m.

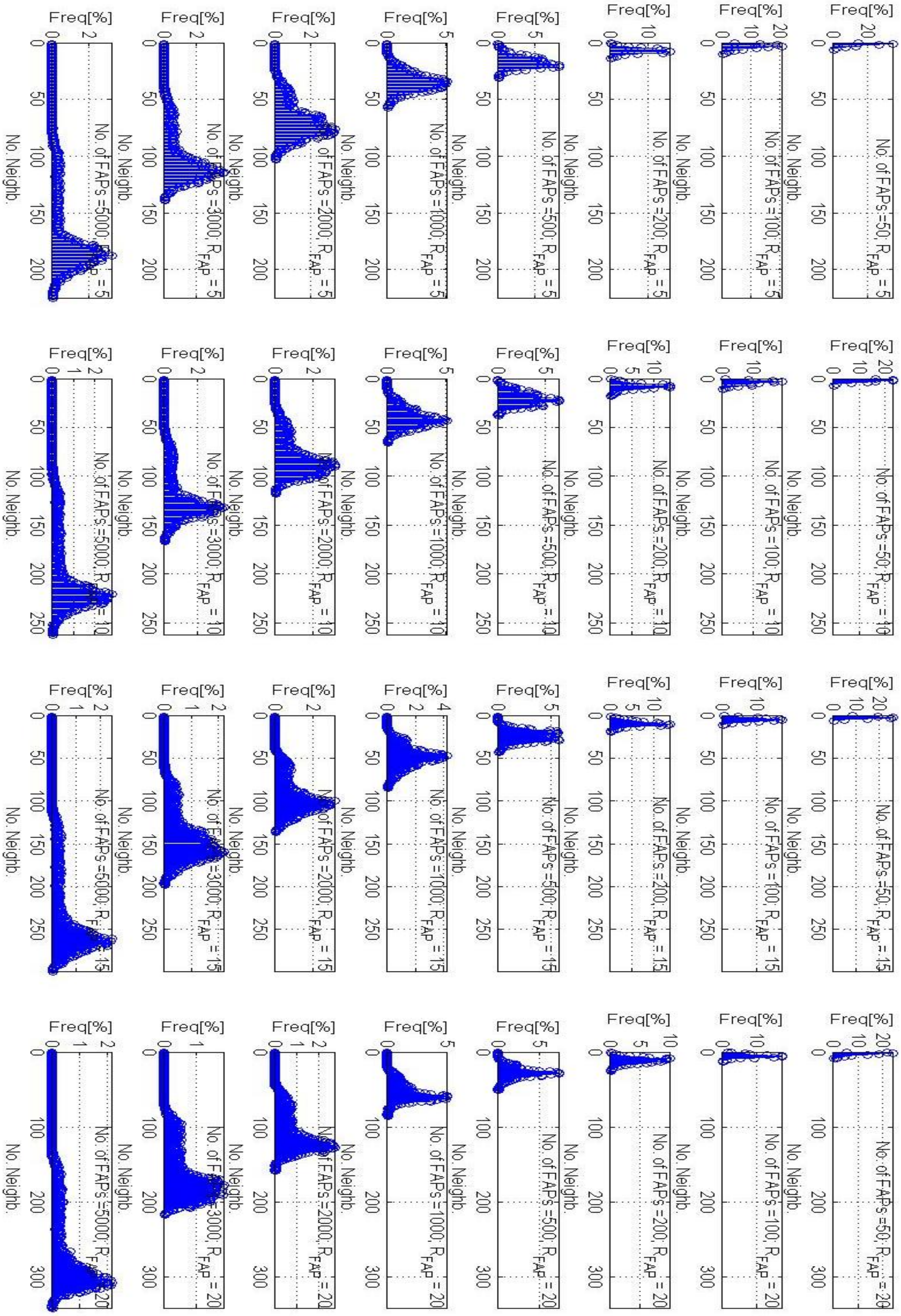

Figure A. 3 RANDM – Percent occurrence of N_{NEIGHB}, offset distance 100 m.

Annex B Cumulative Distribution Functions in DUM

There listed additional figures with Cumulative Distribution Function (CDF) for number of neighbouring cells deployed in DUM with various street width. The x-axis represents a number of neighbouring cells for a newly introduced femtocell among N other FAPs and the y-axis is CDF. Values of number of pre-deployed FAPs and their radius are referred as parameters.

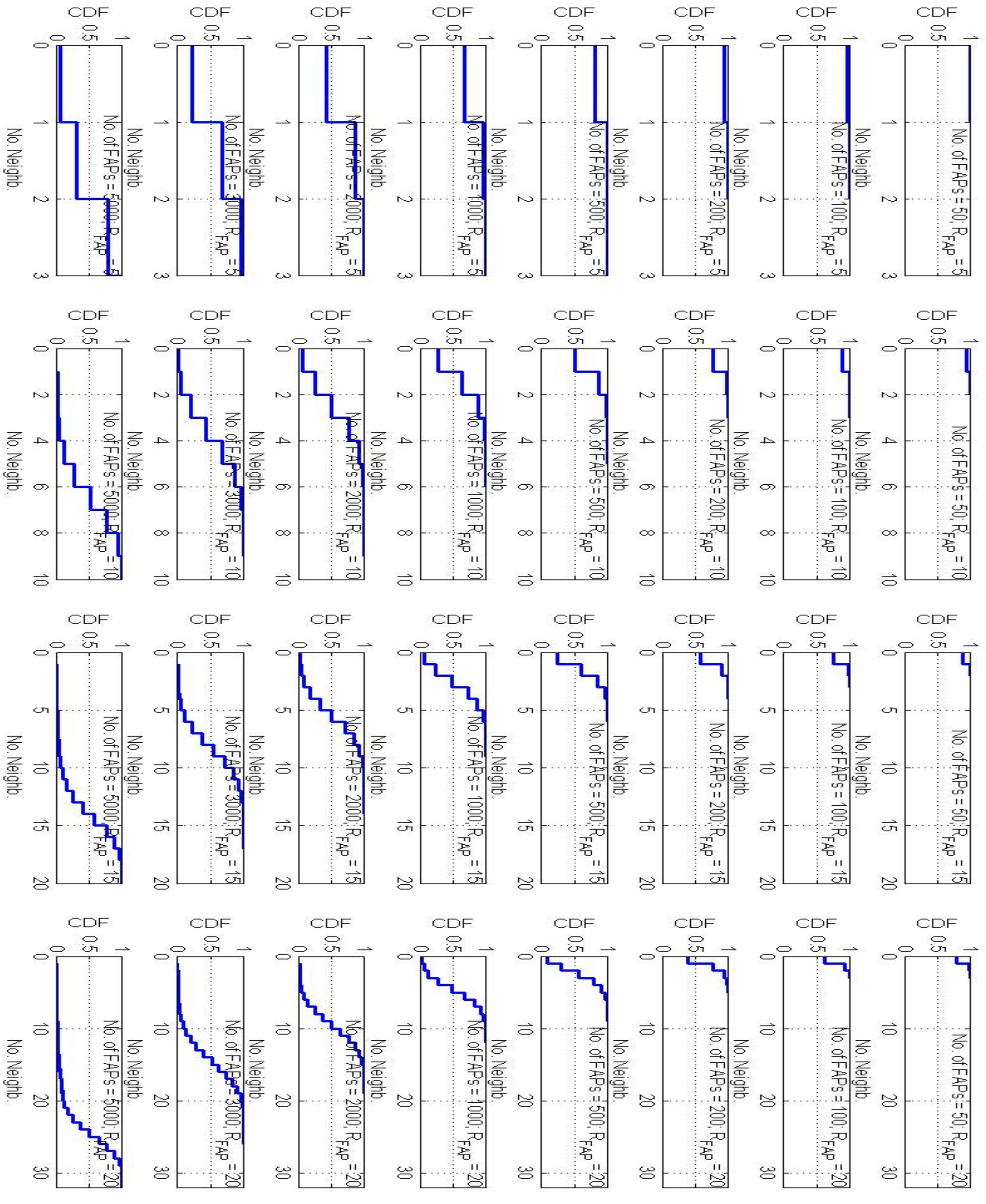

Figure B. 1 DUM – CDF of number of neighbours for street width 5 m.

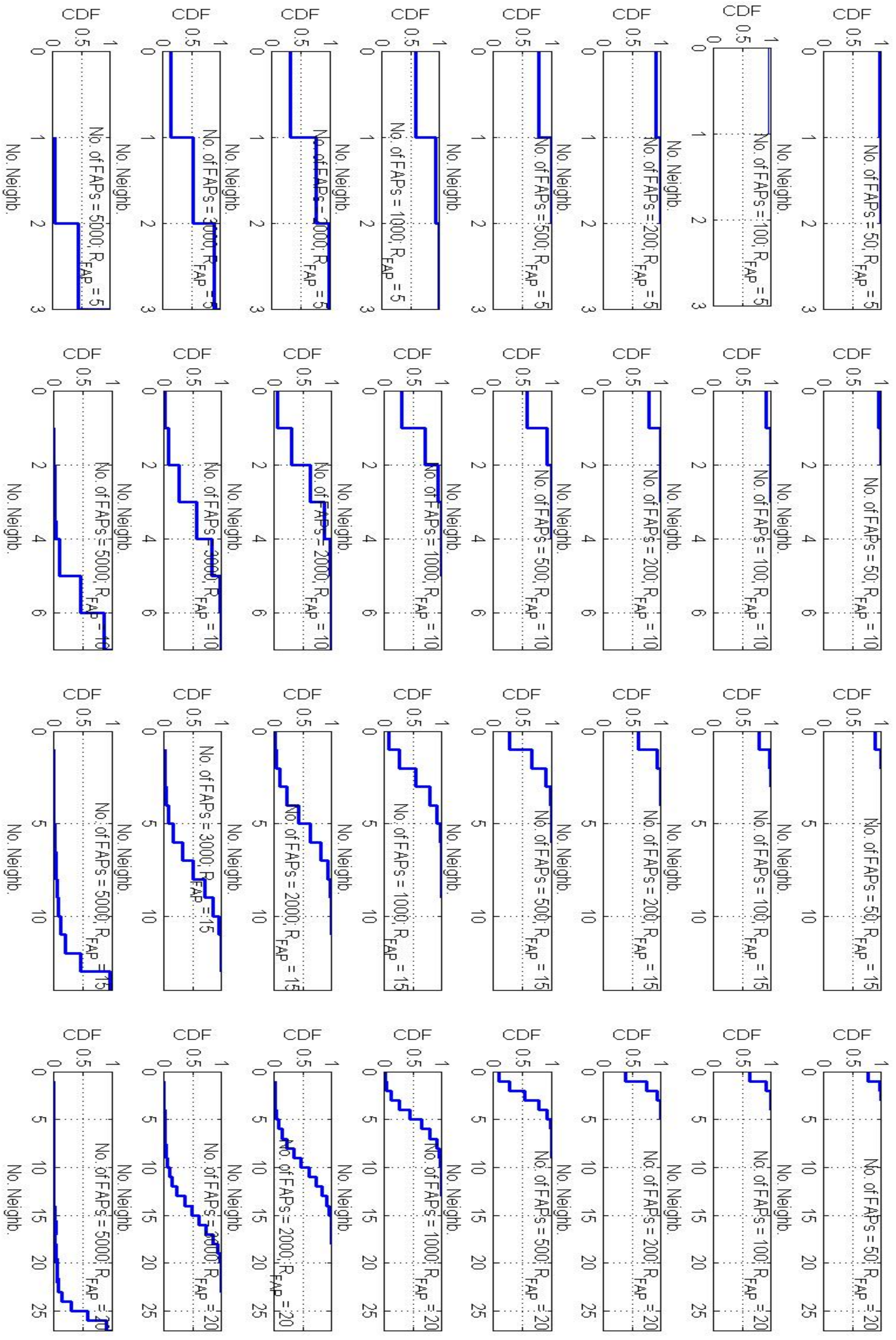

Figure B. 2 DUM – CDF of number of neighbours for street width 10 m

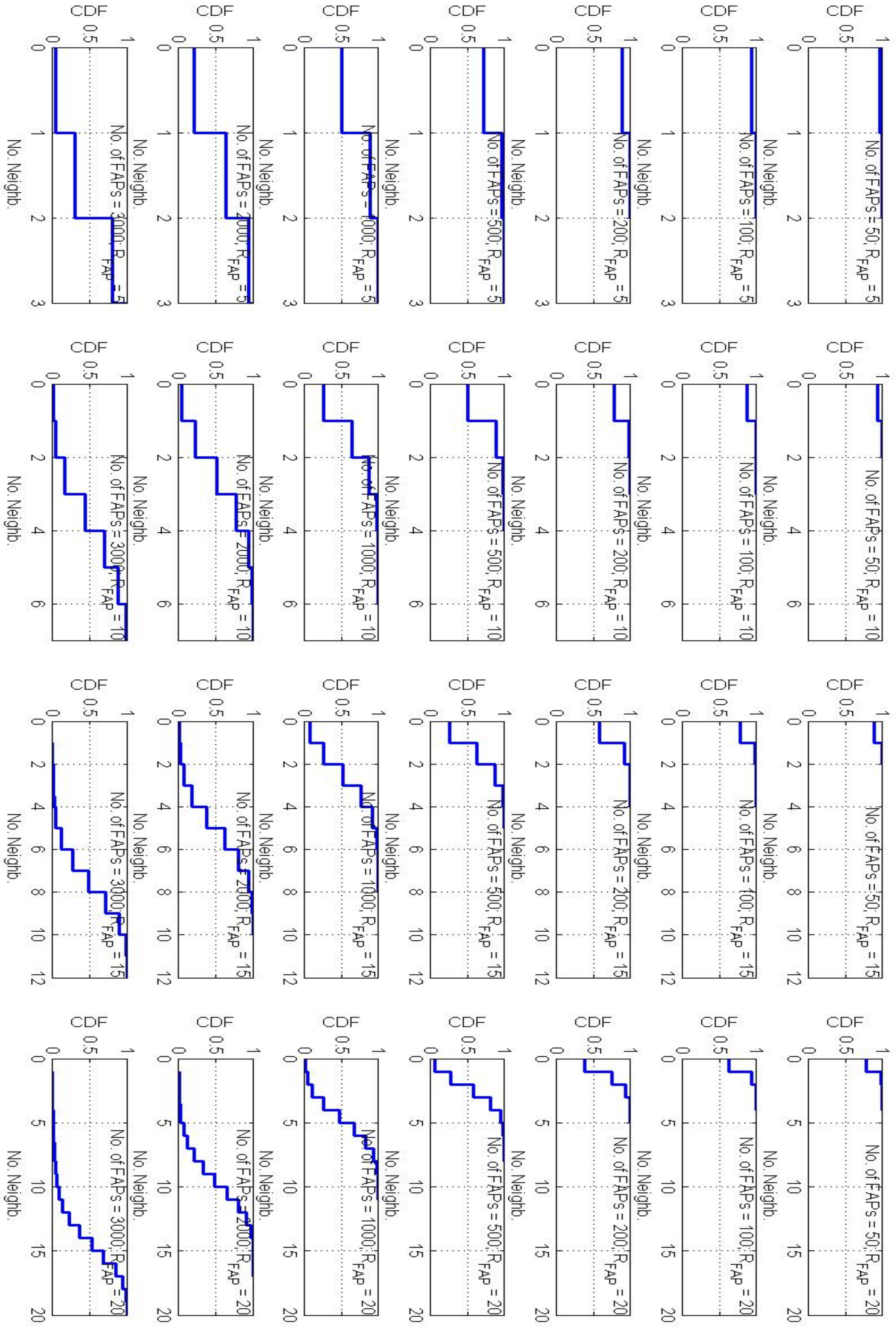

Figure B. 3 DUM – CDF of number of neighbours for street width 15 m

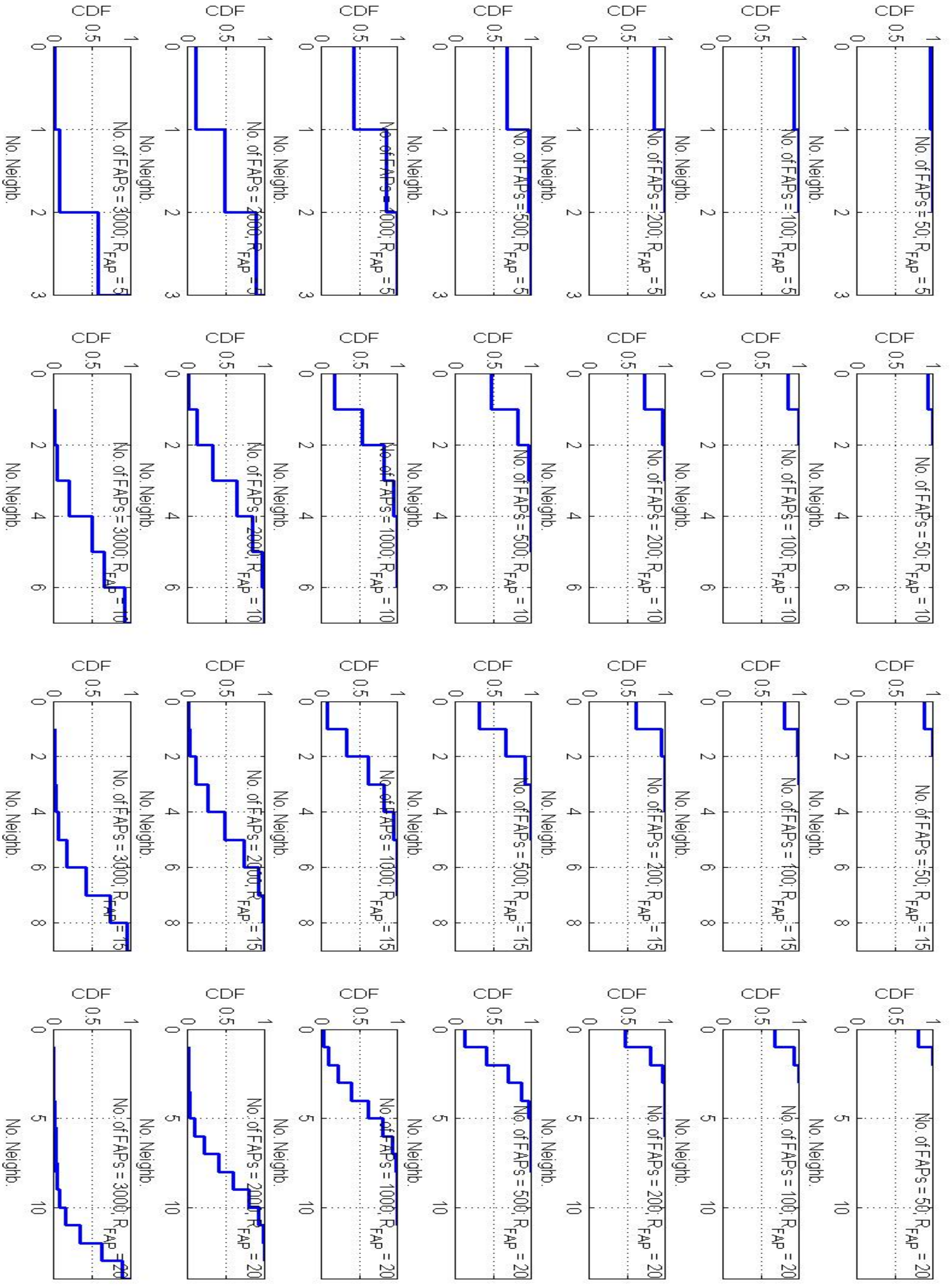

Figure B. 4 DUM – CDF of number of neighbours for street width 20 m

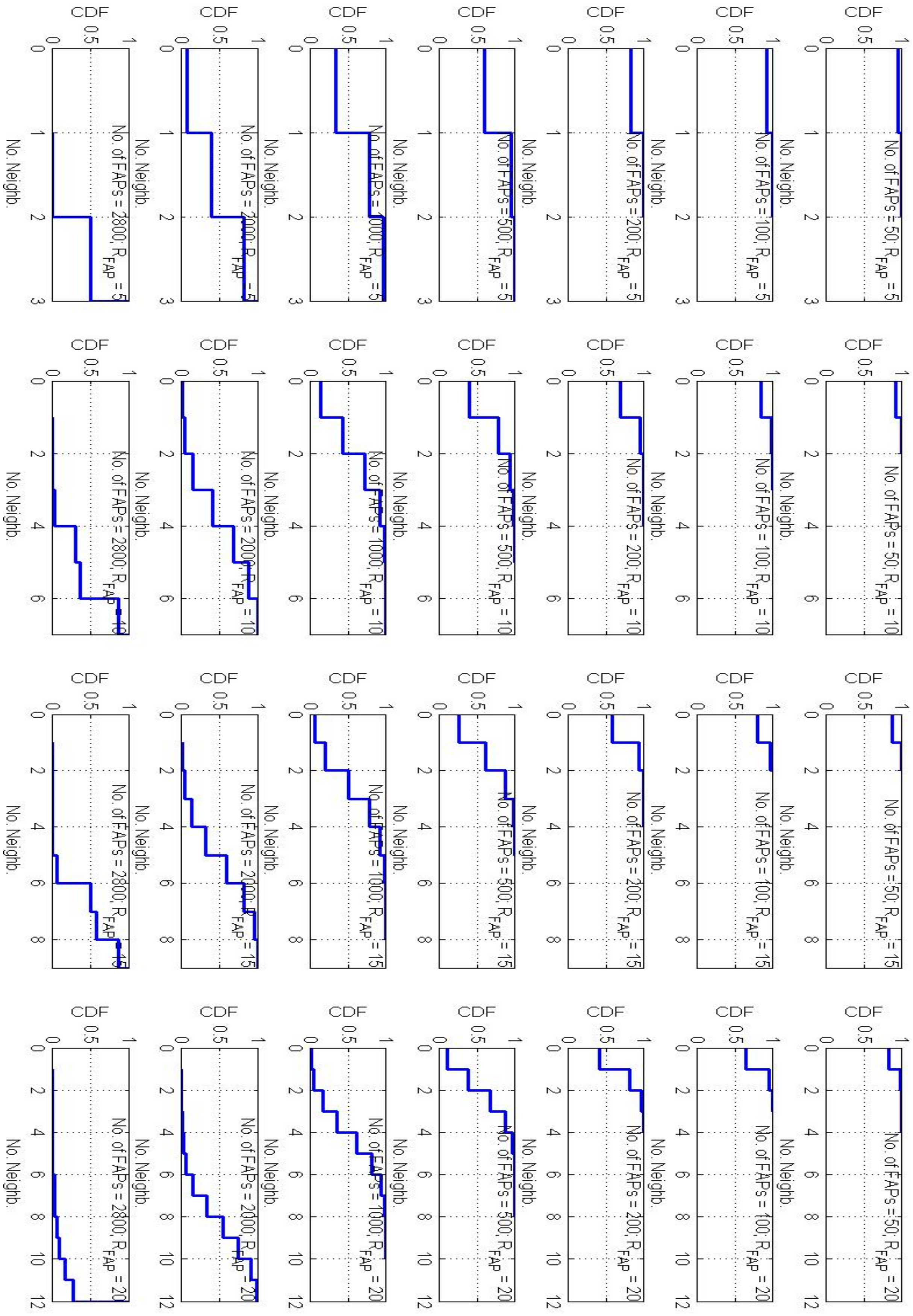

Figure B. 5 DUM – CDF of number of neighbours for street width 25 m

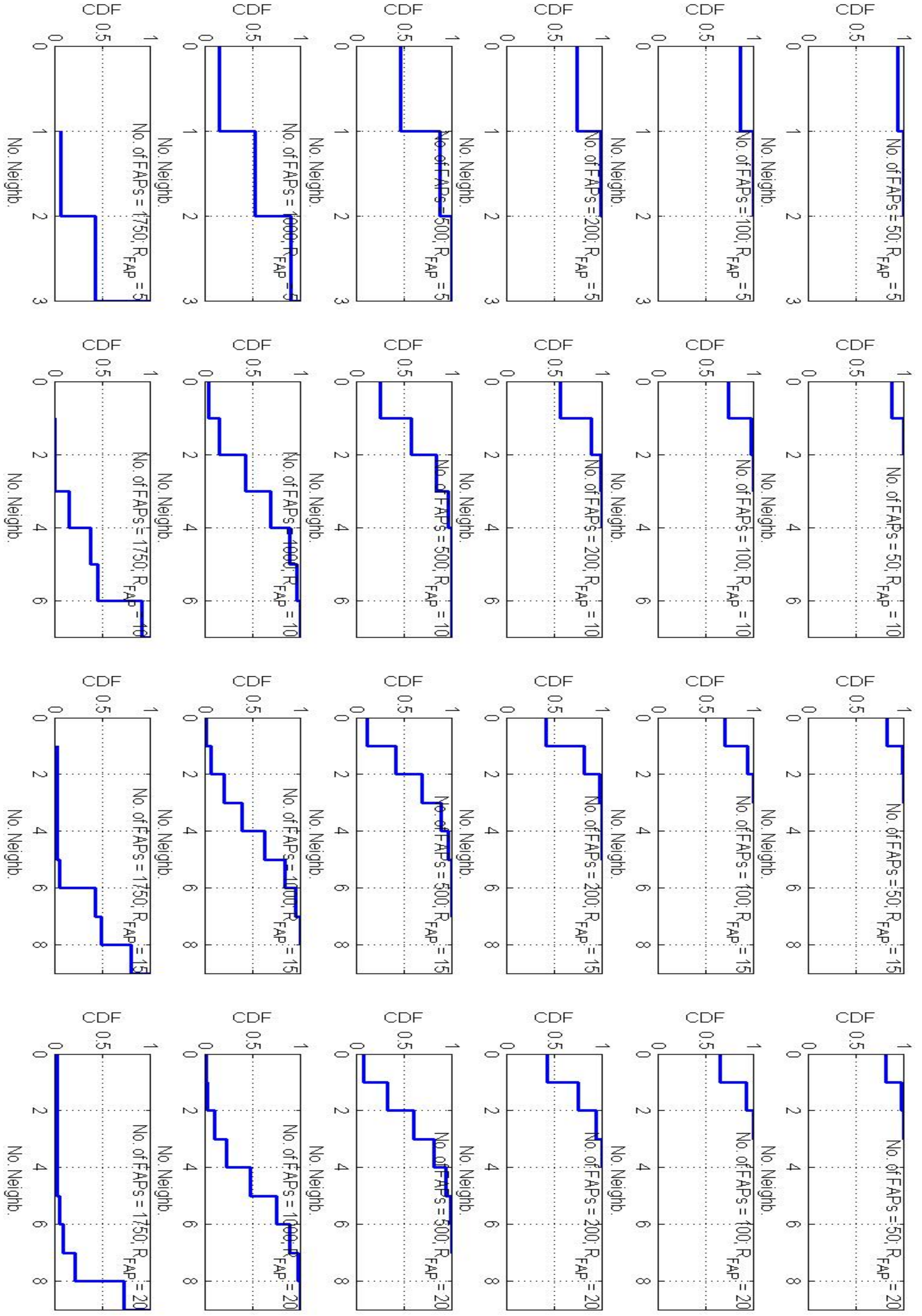

Figure B. 6 DUM – CDF of number of neighbours for street width 40 m.