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Faculty of Electrical Engineering

Doctoral Thesis

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Department of Telecommunication Engineering

Allocation of Resources in Network with Small Cells

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Abstract

To improve communication capacity of cellular wireless network, the massive deployment of small cells is necessary. However the dense deployment of small cells rapidly raises the number of handovers in cellular network. It leads to an increase in overhead and to a rise in probability of handover drop. Therefore, the majority of approaches described in literature focus on the mitigation of handovers to small cells. However, this mitigation leads to an underutilization of resources provided by small cells. One of the main objectives of this thesis is to maximize time spent by users connected to the small cells in exchange for cheaper services provided via small cells. It leads to maximization of utilization of resources of small cells. Concurrently, macrocells are offloaded and they can provide more resources for users without possibility to connect to the small cells. As the results show, the user who does not require high quality of service spent more time connected to the small cells and neighboring macrocells are offloaded.

Another problem in network with small cells is related to management of list of base stations suitable for handover. In a conventional network composed of macrocells only, this list can be created manually. However, with the massive deployment of small cells, this approach is no longer suitable. Therefore, another objective of this thesis is to optimize the list of base stations in users' neighborhood. The proposed algorithms exploit the statistical information on performed handovers in the past to determine the possibility of transition to the neighboring cells. Moreover, for reduction of excessive number of neighbors of the macrocells, the knowledge of the last visited cell in combination with principle of obstructed paths is exploited. As the results show, the proposed algorithms significantly reduces the number of neighboring cells for scanning while the probability of missing handover target cell is kept negligible. After the list of neighbors is set up, cells in the list are scanned. The objective of the proposed scheme for scanning is to maximize utilization of small cells and to minimize energy consumption caused by the scanning. The proposal exploits graph theory to represent a principle of obstructed paths in combination with knowledge of previous visited cell and estimated distance between cells. As the results show, the proposed algorithm reduces energy consumption due to scanning and enables higher exploitation of small cells and consequent offloading of macrocells.

With expansion of smart mobile devices, also the requirements of mobile users on computational demanding applications rise. Since the mobile devices with limited energy and computational capacity are not able to provide sufficient computational power, the need for offloading of computation to a cloud is a convenient way. To reduce data delivery delay caused by a conventional cloud, small cells equipped with additional computing capacity and enabling distributed computation is introduced. In this thesis, the algorithm selecting the computing cell based on combination of users' requirements and the status of cloud is proposed. As the results show, the proposed algorithm is able to provide higher satisfaction comparing to competitive approaches for all types of backhauls while the balancing of load is not significantly affected.

Anotace

Pro zvýšení kapacity mobilní sítě je nezbytné masivní nasazení malých buněk. Avšak se vzrůstající hustotou malých buněk v síti výrazně stoupá i počet handoverů. Velký počet handoverů vede k nárůstu režie komunikace a ke zvýšení pravděpodobnosti chybně provedeného handoveru. Z toho důvodu cílí většina návrhů, popsaných v literatuře, na snížení počtu handoverů k malým buňkám. Avšak toto potlačení handoverů vede k nižšímu využití komunikačních prostředků poskytovaných malými buňkami a v důsledku toho ke zbytečnosti jejich nasazení. Jedním z hlavních cílů této práce proto je prodlužování času stráveného uživatelem při připojení k malým buňkám výměnnou za levnější služby poskytované prostřednictvím malých buněk. To vede ke zvýšení využití komunikační kapacity malých buněk, zatímco makrobuňky jsou odlehčeny a mohou poskytovat větší množství přenosových prostředků pro ostatní uživatele. Jak je zřejmé z výsledků, uživatelé, kteří nevyžadují služby vysoké kvality, jsou ochotni strávit více času připojeni k malým buňkám, což vede k odlehčení makrobuněk v okolí.

Další problém souvisí se správou seznamu okolních buněk vhodných pro provedení handoveru. V konvenční síti složené pouze z makrobuněk může být tento seznam vytvářen manuálně. Avšak s masivním nasazením malých buněk není možné tento přístup použít. Proto je dalším z cílů této disertační práce optimalizace seznamu okolních buněk. Navržený algoritmus využívá statistických informací v minulosti provedených handoverů pro určení pravděpodobnosti přechodu k dané sousední buňce. Navíc je pro snížení nadměrného počtu sousedních buněk makrobuňky využito znalosti předešlé navštívené buňky v kombinaci s principem přehrazených cest. Jak je z výsledků patrné, navržený algoritmus výrazně snižuje počet sousedních buněk určených ke skenování, zatímco pravděpodobnost vynechání buňky vhodné pro provedení handoveru je zanedbatelná. Po vytvoření seznamu okolních buněk dochází k jejich skenování. Hlavním cílem návrhu je maximální využití malých buněk a snížení spotřeby energie využité na skenování. Návrh využívá poznatků z teorie grafů pro reprezentaci principu přehrazených cest v kombinaci se znalostí předchozí navštívené buňky a odhadu vzdálenosti mezi buňkami. Výsledky ukazují, že navržený algoritmus snižuje spotřebu elektrické energie využívané pro skenování a zároveň umožňuje vyšší využití malých buněk a následné odlehčení makrobuněk.

S nárůstem počtu chytrých mobilních zařízení se objevují požadavky uživatelů na zpracování výpočetně náročných aplikací. Protože však mobilní zařízení s omezenou výpočetní kapacitou a kapacitou baterie nejsou schopna poskytnout dostatečný výkon, jeví se jako vhodná alternativa využití výpočetního výkonu cloudu. Pro zajištění nejnižšího zpoždění byly představeny malé buňky vybavené výpočetní kapacitou umožňující provádění distribuovaných výpočty. Algoritmus navržený v této práci vybírá výpočetní buňky na základě kombinace požadavků uživatelů a celkového stavu cloudu. Výsledky ukazují, že navržený algoritmus je schopný poskytnout vyšší úroveň spokojenosti uživatelů se službou v porovnání s ostatními algoritmy pro všechny typy připojení buňky, zatímco rozložení zatížení mezi jednotlivými buňkami není výrazně ovlivněno.

Souhlas se zveřejněním disertační práce

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Zveřejnění může předcházet obhajobě práce i recenznímu řízení.

Zároveň prohlašuji, že tato práce neporušuje autorská práva třetích osob a že jsem si vědom toho, že případné přihlášky k patentové ochraně je třeba podat před zveřejněním práce.

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ACA	Application Considering Algorithm
ADSL	Asymmetric Digital Subscriber Line
ANR	Automatic Neighbor Relation
ASF	Autonomous Search Function
BIM	Background Inter-frequency Measurement
CINR	Carrier to Interference plus Noise Ratio
$CINR_{OL}$	Carrier to Interference plus Noise Ratio Outage Limit
CSG	Closed Subscriber Group
DBS	Distance-Based Scanning
DNC	Distant Neighbor Cell
DSR	Detected Set Reporting
eNB/eNodeB	base station (notation according 3GPP)
FAP/HeNB	Femtocell Access Point/Home eNB
FBSS	Fast Base Station Switching
FCS	Fast Cell Selection
FIFO	First In First Out
GPON	Gigabit Passive Optical Network
HDT	Handover Delay Timer
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
MAC	Medium Access Control
MDHO	Macro Diversity Handover
MeNB	Macro base station
MME	Mobility Management Entity
MSE-BS	Mobility State Estimation-Based Scanning
MUE	User Equipment served by MeNB
NCL	Neighbor Cell List
NRT	Neighbor Relation Table
OP	Obstructed Path
PoI	Point of Interest
QoS	Quality of Service
RAT	Radio Access Technology
RSSI	Received Signal Strength Indication
SCC	Small Cell Cloud
SCeNB	Small Cell

SCeNBce	cloud-enabled SCeNB
SCM	Small Cell Cloud Manager
SCUE	User Equipment served by SCeNB
SON	Self-Organizing Network
TNCL	Temporary Neighbor Cell List
TTT	Time-To-Trigger
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
VM	Virtual Machine
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMM	Wireless Mobility Management

1. Introduction

In wireless cellular networks, a user's mobility is ensured by reconnection of User Equipment (UE) between base stations (in 3GPP LTE-A denoted as eNodeB or eNB). The reconnection is called handover (also denoted as handoff). Handover manages the change of current serving station to proper target station during user's movement across the cells boundaries.

Basically, two types of handover can be distinguished: hard handover and soft handover. If the hard handover is performed, the UE firstly closes all connections with current serving eNB. As soon as the connections to the serving eNB are terminated, new connections with the target eNB are established. Therefore, this type of handover is also known as break-before-make since a short interruption in communication between the UE and the network is introduced. It results in a decrease in user's throughput as no data are transmitted during this break [1]. More than that, Quality of Service (QoS) experienced by users is also lowered [2]. The duration of handover interruption depends on the management message flow exchanged between the UE and the network. Thus the length of interruption depends on several factors such as used wireless technology, e.g., 3GPP Universal Mobile Telecommunications System (UMTS), Long Term Evolution (LTE), or IEEE 802.16e Worldwide Interoperability for Microwave Access (WiMAX), physical layer frame length or network load. In general, the duration of interruption varies from tens to hundreds of milliseconds in third generation networks according to IEEE 802.16e WiMAX or UMTS networks. However, with increasing user's requirements on QoS, the maximum interruption should be shorter than 60 ms in fourth generation networks such as 3GPP Long Term Evolution - Advanced (LTE-A) [3] or Mobile WiMAX Release 2 (denoted also as WirelessMAN-Advanced) [4].

The second type of handover, soft handover, enables simultaneous connection of one UE to several eNB. Consequently, no handover interruption is observed by users during communication. This handover is also known as make-before-break. The soft handover can be implemented as a Macro Diversity Handover (MDHO) or a Fast Cell Selection (FCS) also denoted as a Fast Base Station Switching (FBSS). Both types of soft handovers are defined in former standards for GSM/UMTS [5] or WiMAX [6] networks. In MDHO, the macro diversity combining of signals received from several eNBs included in active set (in WiMAX denoted also as diversity set) is performed. The significant drawback of this approach is high complexity and complicated implementation. The FCS is based on selection of data out of the data received simultaneously from all stations included in the active set. Even if the implementation is simpler comparing to MDHO, it is still essentially more complex than in case of hard handover as this assumes time synchronization of all eNBs in active set. Therefore, hard handover is considered as mandatory in mobile networks while soft handovers are optional. Thus this work considers only hard handovers.

The handovers are controlled via management messages of Medium Access Control (MAC) layer. The management message flow is standard dependent. Hence, the overall overhead generated due to a handover procedure can also vary for each standard, scenario or network status as in case of handover interruption. In general, the overhead originated due to handover is roughly in kilobits (see e.g. [6] or [7]).

In general, the handover can be carried between several types of eNBs in cellular wireless networks. The main criterion for classification of different types of eNBs is transmission power and thus coverage area of eNBs. To cover large areas, the conventional Macro eNBs (MeNBs) can be used. However with the expansion of the coverage area, the communication resources available per user are lowered since they are shared between all UEs connected to the eNB and, moreover, the signal from MeNB is attenuated more significantly. This can lead to low throughput experienced by users; consequently, users' satisfaction can be reduced. The solution of this issue can be a usage of wider bandwidth with more communication resources. However, this approach brings many technical and also economical limits [8].

Another options how to improve throughput is dense deployment of eNBs with low transmission power. Due to the low transmission power of these eNBs, also the coverage area is relatively small. Therefore, these stations are denoted as Small Cells (SCeNBs). Deployment of the SCeNBs into existing mobile networks can improve throughput and QoS for users [9]. A shorter distance between the UE and the SCeNB leads also to a lower energy consumption of the UE. From an operator point of view, the main benefit of the SCeNBs consists in offloading of the MeNBs. Therefore more resources are available for users who cannot connect to SCeNBs.

The deployment of additional tier of SCeNBs into networks introduces a number of problems related especially to the mobility management [10]. Hence, the main objective of this thesis is to give a solution to major issues related to the handover procedure in networks with SCeNBs. One of the main objectives is to maximize the utilization of SCeNBs' communication resources. Maximization of utilization of SCeNB's communication resources is achieved by prolongation of time spent by UE in SCeNBs. For users, who prefer longer time of connection to SCeNBs, the cheaper services are provided. Moreover, maximization of time in SCeNBs leads to offloading of MeNBs. Therefore, more communication resources of MeNBs remain for users without possibility of connection to SCeNBs.

Another objective of this thesis related to handover procedure is ensuring of proper neighborhood scanning process. This issue is addressed by algorithms of efficient creation of list of eNBs in neighborhood for both, new installed SCeNB as well as for new installed MeNB. For more efficient scanning process, new algorithm based on distance between eNBs is proposed. The objective of the proposed scheme is to maximize utilization of small cells and to minimize energy consumption due to scanning. The proposal exploits graph theory to represent a principle of obstructed paths in combination with knowledge of previous visited cell and estimated distance between cells.

Besides the issues, the deployment of SCeNBs opens also new possibilities of their exploitation not only as communication node. Therefore this thesis is focused also on the future direction of using of SCeNBs by means of provisioning of distributed cloud computing services.

In this area, the thesis describes novel approach for selection of SCeNBs for computation while the balancing of load among all clustered SCeNBs is ensured. For simulation, the different backhaul connection of SCeNBs is taken into account.

The rest of the thesis is organized as follows. Next Chapter shows an overview of specifics and problems that are introduced by deployment of the SCeNBs and, the Chapter gives also the motivation for their solving. In Chapter 3, the pros and cons of existing approaches defined in standards and described in literature are summarized. Chapter 4 provides a description of the simulation models and environment together with methodology and simulation scenarios used for later evaluation of the proposed algorithms. In Chapter 5 and Chapter 6, the approach for maximization of utilization of SCeNBs’ resources and the approach for efficient scanning of neighboring cells suitable for handover are presented, respectively. In these Chapters also the comparison with existing algorithms is provided to prove an efficiency of the proposed algorithms. An algorithm for selection computing SCeNBs in future networks with small cells enhanced by computing capabilities is described in Chapter 7. Finally, Chapter 8 summarizes the main benefits of proposed algorithms and outlines possible future work in this field.

2. Background of networks with small cells

In this Chapter, the brief introduction to the SCeNBs and to the specifics of network with the SCeNBs is presented. Moreover, the main issues caused by deploying of SCeNBs into existing cellular networks are identified and the motivation for solving of these problems within this thesis is outlined.

2.1 Small Cells

Small Cells denoted as SCeNBs are small base stations with low transmission power and, hence, relatively small area of coverage. Typical coverage range of SCeNB is from tens to several hundreds of meters. With limited coverage, also the number of covered UEs is limited in comparison with large-coverage MeNB. However, main advantage of the SCeNBs lies in easy deployment with minimum capital and operational expenditures in comparison with building of big tower enabling large coverage, such as MeNBs [8]. Dense deployment of the SCeNBs allows improving total throughput capacity of network in areas with low level of signal from MeNBs or in places with high concentration of users [11]. Improving network capacity results in rising of QoS for users and in offloading of MeNBs' resources.

The SCeNBs cover femtocells denoted as Femtocell Access Points (FAPs) or Home eNBs (HeNBs), picocells and microcells [11]. Whereas the difference between picocells, microcells, and conventional MeNBs lies only in difference coverage range, concept of HeNB brings additional new specifics to common cellular network.

In general, the HeNB is a low-power and short-range base station for home or office utilization. The main purpose of the HeNBs is to improve signal quality indoor or in shadowed areas, to increase throughput in areas with high density of users, and to offload the MeNBs while higher frequencies are utilized (e.g., 2 GHz). The HeNB can operate in present mobile wireless networks as well as in a new generation networks such as LTE-A.

The main difference between the HeNB and other types of SCeNBs is that the HeNB communicates with the core of operators' network over a common broadband connection, such as, cable modem, digital subscriber line, optical fiber, or a separate radio frequency backhaul channel. Moreover, whereas the MeNBs are completely in charge of the operator, the HeNBs are partially controlled by their owners. The owners can turn on and off the HeNB disregarding the connection of other users. The owners can also determine the position HeNB inside user's premises according their preference [12]. Together with mainly indoor deployment, this leads to problem with exact determination of the position of HeNBs and thus to issues with mobility management.

Furthermore, the HeNB can offer three different types of user's access: open, closed, and hybrid [13]. All users in the coverage of a HeNB can connect to this HeNB if it operates in the open access mode. In other words, the HeNB is working as common MeNB or SCeNB in the open access mode. This way, the HeNB can offload the MeNB by serving several outdoor users. However as in case of other types of SCeNBs, a large number of the HeNBs in the network can increase amount of initiated handovers and decrease QoS of users. Contrary, in case of the closed HeNB, only few members listed in so-called Closed Subscriber Group (CSG) can exploit the HeNB’s resources. The owner can decide, independently on the operator, to whom the access is granted [14]. The CSG list may consist of, for example, family members or employees of a company where the HeNBs are installed. All other non-CSG UEs suffer from interference introduced by this HeNB. In the hybrid access mode, a part of resources is dedicated for the CSG users and the rest of the unused bandwidth can be shared by other non-CSG users. The specifics of HeNB’s accesses are thoroughly described latter in subsection 2.2.2 dealing with handovers in network with SCeNBs.

Note that the main objective of this thesis is to propose algorithms usable generally for network with SCeNBs. However, some proposals are originally designed specifically for network with HeNBs. In such cases, note that only the open access of HeNBs is considered. It means all methods designed for HeNBs can be used also for other types of SCeNBs.

2.2 Handover procedure

This section is split into two subsections and describes the basic principle of handover procedure in wireless mobile networks. First, the general handover procedure in network without SCeNBs is explained. Further, the specific aspects of handover in network with SCeNBs are introduced.

2.2.1 Handover principle in conventional network without SCeNBs

The major purpose of handover in mobile networks is either to ensure continuous connection with required QoS or to balance load in network. The procedure of handover in LTE-A network is composed of three stages [15]: handover preparation, handover execution, and handover completion. To determine the optimum time instant for performing handover, the channel conditions are continuously monitored by the UE. If the UE is connected to network, the UE sends measurement reports to its serving eNB. The measurement reports contain information on signal quality of serving eNB as well as signal quality of eNBs in UE’s vicinity. Cells in UEs vicinity are included in so called Neighbor Cell List (NCL) and this stage prior the handover is known as the neighborhood scanning. The measurement reports are sent back to the network. The reporting can be performed either periodically or even triggered.

Based on measurement reports, the serving eNB can decide to initiate procedure of handover preparation to the neighboring eNB, which is able to provide higher signal quality. Such eNB is denoted as target eNB. In the simplest case, the samples of signal levels received from the neighboring eNB are compared and the handover is initiated if:

$$\overline{s}_t[k] > \overline{s}_s[k] + \Delta_{HM} \quad (1)$$

where Δ_{HM} represents the hysteresis margin, $\overline{s}_t[k]$ corresponds to the signal level received from target eNB, and $\overline{s}_s[k]$ is the signal level received from current serving eNB. Besides hysteresis margin Δ_{HM}, also Time-To-Trigger (TTT) can be considered in handover procedure. This parameter is represented by a time interval (in Figure 1 denoted as TTT) between fulfillment of (1) and the initiation of handover. This approach is used to eliminate redundant handovers performed, e.g., due to fast fading or due to so-called ping pong effect (continuous switching of the UE between two serving eNBs).

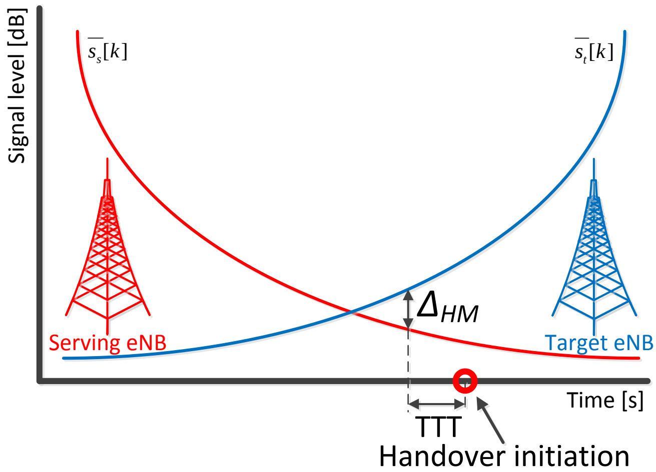


Figure 1: Conventional handover decision

During the handover preparation stage, the serving eNB contacts the target eNB and establishes tunnels for uplink data forwarding and downlink data forwarding. Once the preparation phase is completed, the execution phase is running. In the execution phase, a handover command control message is sent by the serving eNB to the UE to notify the UE that it is going to be reconnected to another eNB. After receiving the command control message, the UE disconnects itself from the serving eNB and requests connection with the target eNB. In the meantime the UE cannot either receive or transmit any data. User data are forwarded from serving eNB to target eNB. This data are queued by the target eNB in the UE buffer.

As soon as the synchronization with the downlink of target eNB is completed, the UE starts the next procedure of handover execution denoted as network re-entry. During network re-entry procedure, the UE is supposed to perform ranging, re-authorization and re-registration. The UE obtains information on uplink channel and ranging parameters, such as, transmitting power, timing information or frequency offset. Once the UE has successfully reconnected to the target eNB, the target eNB transmits all the buffered data of the UE. After successful authorization and registration, the UE can continue with normal operation.

The handover procedure is finished by completion phase after which the UE sends a handover complete message that indicates this handover is completed to the new serving eNB.

The main purpose of the completion phase is to release all the resources used by the UE at the previous serving eNB and to notify the upper layer to switch the path of the packet to the new serving eNB. Therefore, the new serving eNB needs to inform the previous serving eNB to release all resources dedicated for the UE and the target Mobility Management Entity (MME) to execute path switching to the new serving eNB, respectively [16]. The process flowchart follows in Figure 2.

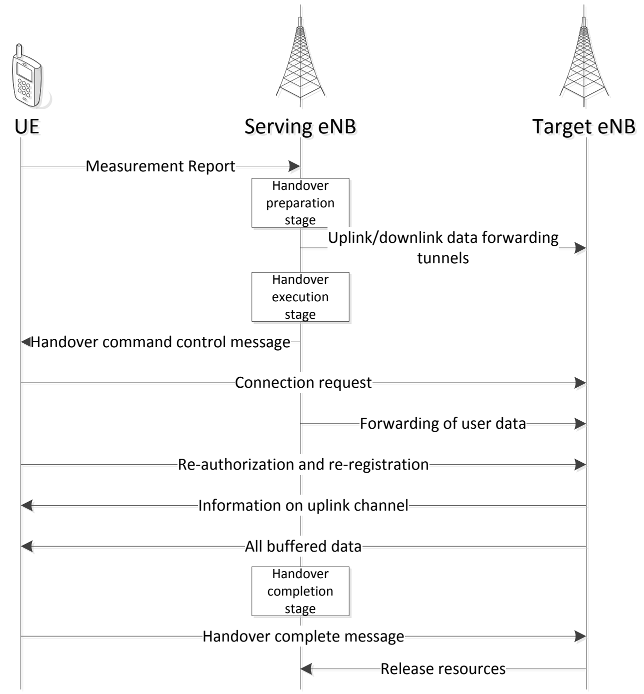


Figure 2: Handover process in LTE-A network

2.2.2 Handover principle in network with SCeNBs

In general, the handover in SCeNBs environment follows the same principle as a conventional handover intended in 4G networks. However, several new aspects and issues arise due to the SCeNBs (and especially HeNB) specifics, such as, very low transmitting power, varying backhaul connection's capacity or high density of SCeNBs deployment. By introduction of the SCeNBs into the network, three new handover scenarios can be distinguished depending on the type of serving and target stations as depicted in Figure 3.

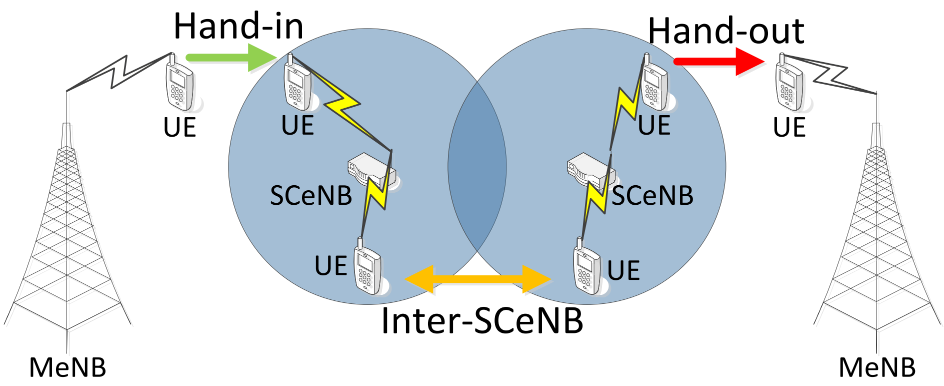


Figure 3: Handover scenarios in environment with SCeNBs

The first type of handover is represented by switching of the UE from a serving MeNB to a target SCeNB. This type of handover is denoted as hand-in. Successful execution of hand-in depends on the available backhaul capacity of the target SCeNB and the ability of satisfying the user. In scenario with HeNBs, the HeNB further admits the UE according to provided type of HeNB's access as explained later in this subsection.

The second type of handover is called hand-out. It is a consequence of the foregone hand-in, i.e., the UE is disconnected from the SCeNB and it is going to be served by the MeNB. Selection of the target MeNB is managed according to a common admission process for handovers. However, the admission procedure should consider the fact that the UE would eventually lose the connection to the SCeNB due to high interference originated from the MeNB if the handover to the MeNBs is not performed.

The last handover type, inter-SCeNB handover, corresponds to the situation when handover from the SCeNB to another SCeNB is executed. For this handover type, the admission procedure follows the similar policies as in case of hand-in.

For the HeNB, to initiate hand-in and inter-HeNB handover, the crucial factor to be taken into account is the access mode of the target HeNB. If the HeNB provides the closed access, only users belonging to CSG are allowed to execute handover to the HeNB. The CSG list is completely managed by the HeNB's owner. As the result, other users served by the MeNB, are denied to access the HeNB if the closed access is utilized. The HeNB's resources are shared only by the CSG members and thus this approach is preferred by customers [17]. On the contrary, the close access introduces several major problems from the perspective of the operator. The major issue is an interference generated by the HeNBs to the UEs connected to MeNBs (MUE), who get close to the HeNB and who are not in the CSG [18], [19]. Therefore, a control algorithm of the HeNB's transmitting power must be implemented to minimize the interference [20], [21], [22].

On the other hand, in case of the open access, the HeNB works the same way as other types of SCeNB and thus in similar principle as a regular MeNB. It means if the HeNB is able to satisfy requirements and demands of the UE, then the UE can perform hand-in. Otherwise, the handover is rejected. In comparison with the closed access, the advantage of the open access scheme consists in significant increase in the network throughput, lower interference and also alleviated MeNB's load. Consequently, the open access is preferred especially by the operators [23].

Nonetheless, the problem of the open access HeNB consists in increasing number of initiated handovers, as in case of other types of SCeNBs. Thereby excessive signaling overhead is generated and the probability of handover delay or even handover failure is increased as well [24]. Therefore techniques for elimination of redundant handovers are used.

The hybrid access of HeNB combines both above mentioned access strategies. While the certain amount of HeNB's resources is dedicated primarily for the CSG users, the rest of HeNB's capacity is available for other users. The hybrid access is the most challenging one from the handover management point of view. The handover decision is strongly related to the rules defined for sharing of the HeNB's backhaul and allocation of radio resources among outdoor and indoor users. The ratio of resources available for outdoor users can be limited to a fixed level. The drawback of this approach is that resources unused by indoor users are wasted. On the other hand, the sharing of whole bandwidth (radio as well as backhaul) can decrease indoor user's QoS. This method is not convenient for indoor users as they have to pay for backhaul connection and thus they should be in some way treated preferentially. Therefore, some sort of compromise must be found. The new algorithms dealing with usability and QoS enhancement for users served by HeNBs with the hybrid access are proposed in [25] or in [26].

2.3 Problems introduced by SCeNBs

As stated before, by introduction of SCeNBs into existing network cellular network, several new problems from perspective of handover and mobility management have to be tackled for their efficient integration. One of the main problems is to find compromise between elimination of redundant handovers caused by dense deployment of SCeNBs and maximization of utilization and exploitation of their available communication resources. The improvement of utilization is the main idea of deployment since it can lead to higher throughput and QoS for users and also to offloading of MeNBs from operators' point of view. Another problem introduced by SCeNBs is related to establishment and maintenance of NCL of both new installed SCeNBs and new installed MeNBs. Proper scanning of NCL leads to ensuring of seamless handover and therefore to reduction of scanning delay, improvement in throughput and QoS, and reduction of energy consumption required for scanning.

Some other problems regarding handover procedure such as reduction of handover interruption or reduction of overhead generated by the handover can be identified. Nevertheless, these issues are not directly related to the deployment of SCeNBs and can be solved by common approaches already investigated for MeNBs in [27] or in [28]. Thus only these two crucial problems are the main objectives of this thesis and are described in detail in following subsections.

2.3.1 Underutilization of SCeNBs

One of the main issues is how to handle a handover procedure [29]. A conventional handover decision based on comparison of signals received from a serving and a target station does not take dense deployment and small serving radius of the SCeNBs into account. A large number of the SCeNBs in a network increases amount of initiated handovers and thus decreases QoS of users.

The high frequency of handovers is caused by the fact that UE may perform multiple handovers even within the same MeNB as it crosses cell boundaries of deployed SCeNBs as can be seen in Figure 4. High frequency of handovers leads to an increase in signaling overhead and a prolongation of handover interruption. The prolongation of interruption results in considerable drop in throughput and lower QoS provided to users and can lead even to a connection drop.

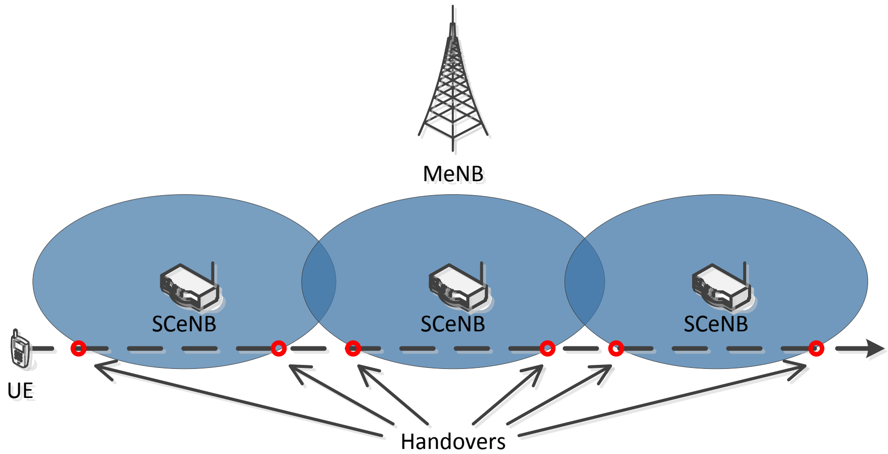


Figure 4: Problem of frequent handovers related to the dense deployment of SCeNBs

In conventional networks without SCeNBs, this effect could be suppressed by common techniques for elimination of redundant handovers. The most widely used are: hysteresis margin Δ_{HM} [30], windowing (also known as signal averaging) [31], and Handover Delay Timer (HDT) [32], which extends conventional TTT [5], [6]. These techniques can be implemented also in networks with SCeNBs as presented, e.g., in [33]. The paper demonstrates drop in a number of redundant handovers by above mentioned techniques. However, these techniques reduce not only amount of handovers, but also a gain in throughput and overall utilization of the SCeNBs [1]. A lower throughput is result of communication with a station providing not the highest channel quality for a time interval before handover initiation. The similar conclusion can be derived from the paper [34]. The authors compare the probability of UE's assignment to the SCeNB that does not provide the highest signal quality. The paper shows a tradeoff between a minimum duration of signal averaging and probability of an error assignment.

Both papers show low efficiency of common handover decision techniques. Hence, there is a need for other approaches for handover decision in networks with SCeNBs which would lead to maximization of utilization of SCeNBs. This, consequently, results to offloading of MeNBs and to reduction of the number of redundant handovers. Therefore, the efficient handover management consisting in proper handover initiation and decision and maximizing the utilization of SCeNBs is proposed in this thesis.

2.3.2 Management of Neighbor Cell List

Another important issue is related to selection of the target cell to which the handover should be performed. To proper initiation of handover, moving users must be able to discover cells in their neighborhood. For this purpose, the users perform neighborhood scanning. To ensure faultless handover procedure of mobile users, each cell in the network must establish a NCL. The NCL contains the list of all neighboring stations, to which handover can be performed as presented in Figure 5. This list is distributed to the UEs served by the given eNBs. All stations included in the NCL should be periodically scanned by UEs with purpose of selection of the most suitable candidates for handover.

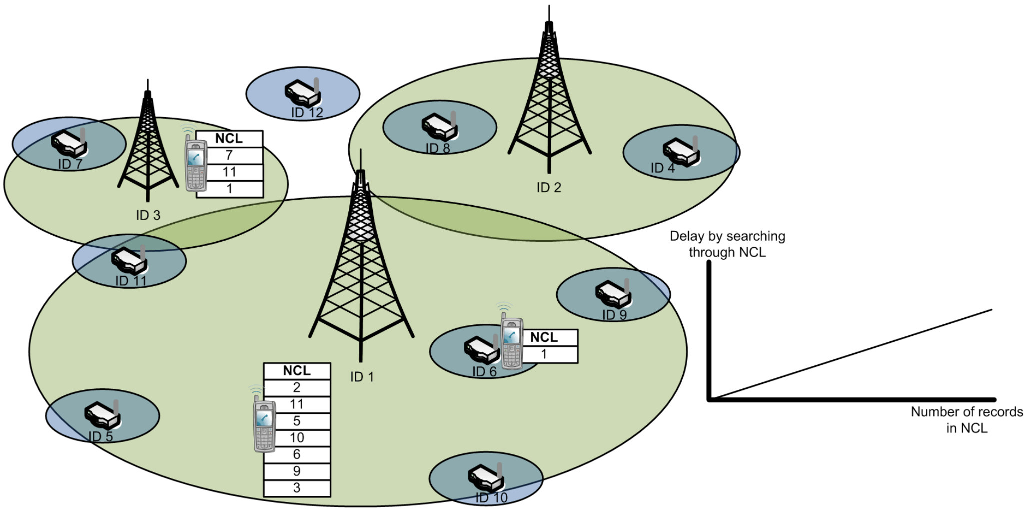


Figure 5: Neighbor Cell List

If the NCL is not used or if user arrives to the place with no signal received from the known cells, the scanning process is significantly prolonged since the scanning of the whole spectrum must be accomplished [35]. This can lead to wasting battery of the UE and to a reduction of user's throughput. It brings also the additional delay since the scanning of the whole bandwidth must be performed continuously until the UE finds a suitable cell. Therefore, the length of the NCL should be maintained as short as possible. Nonetheless, the NCL has to include all surrounding cells. If any of neighbors is not included in the NCL of the given eNB, the transition of the UE to that cell will lead to the handover failure [36].

On the other hand, if the UE scans an excessive number of neighboring cells, which are not the current neighbors, time for finding the most appropriate candidate for handover is significantly increased [37]. It results in wasting battery power of the UE [38], reducing throughput of users, and lowering QoS due to the more frequent occurrence of measurement gaps in data transmission [39]. The scanning of a high number of cells occurs especially when a large number of the SCeNBs within a range of a MeNB is deployed. By using conventional methods for neighborhood scanning, all cells deployed in the range of MeNB are considered as regular neighbors of the MeNB. Therefore, all these cells should be scanned as potential handover candidates.

For the cases if the SCeNBs are not deployed in network, the records are added to the NCL either manually during the installation of the cell based on the position of the cell or automatically on the basis of calculating signal propagation in a particular environment. However, this procedure cannot be efficiently used when the SCeNBs are deployed. In case of the HeNB, neither the operator nor the network is generally able to determine the HeNB's position and impact on signal levels in HeNB's neighborhood. The main reason is that the HeNB can be placed at any location within the house depending on customer's requirements. Moreover, the location of HeNBs does not have to be necessarily fixed but it could be changed from time to time. Therefore, the neighboring HeNBs cannot be determined as easily as in conventional networks with MeNBs [35].

By using algorithm for the NCL creation described in standards or in literature for the MeNBs, the SCeNBs is not able to determine the number of neighboring cells suitable for handover. Simultaneously, by using the conventional method for creation and maintenance of the NCL of MeNB in network with the SCeNBs leads to extensive number of neighboring cells to be scanned. In other words, the determination of neighboring cells is not efficient since some neighboring cells can miss in the NCL and also some cells can be in the NCL unnecessarily if the conventional approaches are used. Therefore, an efficient creation and maintenance of the NCL is one of the main problems to ensure the seamless handover between all eNBs in network with SCeNBs.

2.4 Exploitation of computational resources of SCeNBs

In recent years, applications requiring high computation capacity are offered to the users. Although the computation capabilities of UEs are still increasing, the computation at the UE can be limited by the capacity of UE's battery due to high energy consumption due to computation [40]. To overcome this problem, a cloud-computing can be exploited. The main advantage of conventional cloud systems is ability to process heavy computation tasks in relatively short time. On the other hand, if the latency is critical factor, the conventional centralized cloud systems cope with a high delay of data delivery from the UE to the cloud [41]. The data for computation as well as computation results must be transferred through the radio access networks, backhaul, operator's core and the Internet to the cloud. Beside data delivery delay, also a congestion of backhaul of mobile networks base stations and operator's core network can be increased by offloading of an application if the centralized cloud system is exploited. Possible solution to reduce load of backhaul as well as operator's core network and, at the same time, to decrease latency of data delivery is to deploy computational capable devices closer to the users.

In mobile networks, the nearest location where a computing capable device can be placed is an eNB. For deployment of additional computing capacity, the eNBs with limited range, such as SCeNBs, are the most suitable due to limited amount of served users and due to proximity to these users. The SCeNBs equipped with additional computing capacity are denoted as cloud-enabled SCeNBs (SCeNBces). The concept employing SCeNBces for offloading of computational demanding applications from mobile users is known as Small Cell Cloud (SCC) [42]. In the SCC, individual SCeNBces are able to cooperate and share their computing power within a cluster of SCeNBces. Computation in each cluster is managed by a Small Cell Cloud Manager (SCM) [42]. The SCM collects and maintains the information about status of all elements in the SCC system including computational power, load of SCeNBces, and status of all communication links within the SCC.

To offload a task to the SCC system, the UE first sends offloading request to the SCM via its serving SCeNBs. This request specifies type of application to offload and contains all important parameters of this application (e.g., amount of bytes to transfer, required handling time, etc.). Based on these parameters, the SCM decides if it is efficient to offload computation from the UE [43], [44]. Subsequently, if the offloading decision is positive, proper SCeNBce(s) is/are selected to process the task. From the user's perspective, the most suitable is to deploy computation at the serving SCeNBce to minimize transmission delay [45] especially if the SCeNBces exploit backhaul with limited throughput. On the other hand, it can lead to a higher computation delay if this cell is already heavily loaded by computation for other users or if it is equipped with only limited computing power. From the SCC perspective, uniform distribution of tasks among all available SCeNBces is profitable to ensure long-term usability of whole system and to guarantee availability of services also for future tasks offloaded by other users. Moreover, uniform distribution of load among SCeNBces also leads to less signaling overhead [46]. To that end, load distribution algorithm considering all specifics of the SCC including radio and backhaul status and computation load of the SCeNBces must be designed.

In literature, the algorithms ensuring uniform distribution of load among all nodes in the system are denoted as load balancing algorithms. The load balancing algorithms can be classified into static and dynamic [47]. If the static load balancing is used, decision on allocation of the computing resources to the SCeNBces is made before the offloading begins. Then, the processing is performed only on the selected SCeNBces. On the contrary, the dynamic load balancing allows more flexible changes in the system during execution of the computation. The dynamic load balancing assumes transfer of computation among SCeNBces during task processing. Although the dynamic load balancing is generally more efficient, migration of tasks can lead to a high amount of data transferred from one Virtual Machine (VM) to another VM [48]. Any change of the VM location (by means of changing the SCeNBce) results in a need of migration of complete VM content including status of memory [49]. Therefore, the VM migration usually implies huge amount of data to be transmitted from one SCeNBce to another via its backhaul. Consequently, the delay due to migration is significant in the SCC where the SCeNBces are typically equipped with backhaul of a limited capacity. On the other hand, the static load balancing is of a low complexity and it generates less overhead [50].

However, by using only load balancing algorithm without considering of application parameters and status of the whole SCC system, the tasks can be assigned to the SCeNBs without sufficient computational capacity. It can lead to reducing of QoS for users and even to failure of tasks. Therefore, the new algorithm suitable for specifics of SCC environment is needed. The objective of the algorithm proposed in this thesis is to increase user's satisfaction with experienced time spent by offloading, including data transfer as well as computation period. At the same time, also the load should be balanced among individual cells equally to minimize overhead.

3. State of the art solutions for networks with SCeNBs

Although the most of the problems introduced by deployment of the SCeNBs into existing cellular network can be solved by approaches designed for network only with MeNBs, several issues that cannot be handled by conventional way still remain. This Chapter gives an overview of existing methods proposed originally for network without SCeNBs and their suitability for SCeNBs as well as the approaches and techniques devised primarily for network with SCeNBs.

3.1 Extension of time spent by users in SCeNBs

If the SCeNBs are deployed, several aspects, such as, low serving radius or higher throughput must be additionally taken into account if the handover decision is designed. These aspects can lead to an increase in amount of signaling overhead generated due to initiation of large amount of redundant handovers. The problem of redundant handovers or lower QoS occurs if users passing close to the SCeNB and they can experience better signal quality from the SCeNB than from the MeNB. In this case, the handover from the SCeNB to the MeNB (hand-in) can occur. Therefore, research papers dealing with mobility in a network with the SCeNBs are usually focused on a reduction of a number of unnecessary handovers.

Enhancement of conventional Δ_{HM}, so called adaptive Δ_{HM}, for scenario with MeNBs is investigated in [51]. The results show significant reduction of area where handover is initiated. However, an assumption of precise knowledge of distance between a UE and its serving MeNB together with assumption of invariant and accurately known radius of MeNBs are not realistic for implementation in real networks. This drawback is more emphasizes if the SCeNBs are deployed. The above mentioned weakness can be eliminated by considering Carrier to Interference plus Noise Ratio (CINR) for adaptation of Δ_{HM} value in SCeNBs as presented in [52]. The actual level of hysteresis is derived according to the next formula:

$$\Delta_{HM} = \max\left\{\Delta_{HM}^{\max} \times \left(1 - 10^{\frac{CINR_{act} - CINR_{\min}}{CINR_{\min} - CINR_{\max}}}\right)^{EXP}; \Delta_{HM}^{\min}\right\} \quad (2)$$

where $\Delta_{HM}^{\max}$ is the maximum value of Δ_{HM} that can be setup (in the middle of the cell); *EXP* represents the exponent; and $\Delta_{HM}^{\min}$ is the minimum Δ_{HM} that can be set up; $CINR_{act}$ is the actual CINR measured by a UE; $CINR_{min}$ and $CINR_{max}$ are minimum and maximum values in the investigated area, respectively. This approach improves user's throughput and enables implementation of adaptive Δ_{HM} to the networks with HeNBs. The proper selection of $\Delta_{HM}^{\max}$, *EXP* and $\Delta_{HM}^{\min}$ is not presented in the paper; however it obviously influences the overall performance.

The adaptation can be considered also for other techniques such as HDT or signal averaging as described in [53]. As the results of both before mentioned papers show, the adaptation is considerable profitable in case of HDT technique and it also slightly improves the efficiency of Δ_{HM}. On the other hand, no gain in performance is observed by adaptation of window size for signal averaging. This fact can be expected since window size is not related to the CINR level.

Another proposal, presented in [54], targets the decrease of number of redundant handovers to the SCeNB by defining two thresholds, one related to the MeNB signal level and the second one related to the SCeNB signal level. To perform the handover to the SCeNB, at least one of the following conditions must be fulfilled: i) signal level of the MeNB must be lower than the first threshold; or ii) signal level of the SCeNB must exceed the second threshold. Last, the signal level of the SCeNB must be above than signal level of the MeNB.

The handover mechanism for SCeNBs considering asymmetry of the SCeNB's and the MeNB's transmitting power is introduced in [55] and further specified in [56]. The main objective of proposed algorithm is elimination of handovers if the SCeNB and the MeNB are near to each other. The mechanism compares the average signal from SCeNB with received signal level from MeNB in case that signal of the SCeNB is under predefined absolute threshold value of –72 dB in the same manner as defines (1). Otherwise, the signal from the MeNB (including Δ_{HM}) is compared with combination of both signals from the MeNB and the SCeNB. Both signals are combined in following manner:

$$s_{pro}^{\alpha}[k] = s_f[k] + \alpha s_m[k] \tag{3}$$

where parameter α decreases with rising distance between the MeNB and the SCeNB. After comparison of individual results, either MeNB or SCeNB is selected as the serving base station. The results show that the probability of UE's assignment to the FAP is increased. Contrary, the amount of handovers is slightly higher when compared to conventional approach. Therefore authors suggest using adaptive hysteresis.

The extension of common techniques for elimination of redundant handovers can be modified or extended. This way is presented for example in [33]. The authors propose a procedure for managing the handover in the hybrid access of HeNB. The proposed procedure takes into account the type of users (CSG or non-CSG), received signal level, duration of the received signal level above the critical threshold, ratio of signal to interference, and radio and backhaul capacity of the HeNB. If the signal received from the HeNBs is being stronger than decision-making level, then it is considered if the UE is pre-registered (members of CSG). If not, the signal received by the UE has to remain stronger than the decision level for more than a certain time *T*. The handover of pre-registered users (members of CSG) is performed immediately after fulfilling the hysteresis level. For all other users, the TTT with significantly prolonged duration is applied. The results show that the amount of handovers is reduced significantly. The proposed method is focusing only on a reduction of the number of handovers, but it ignores the possible interference and negative impact on user's throughput which is supposed to be significant.

The second way for elimination of handovers is represented by inclusion of other conditions to the handover decision stage. The possibility of eliminating unnecessary handovers and signaling overhead according mobility states of users is described, for example, in [57], [58] and [59]. Authors of [57] introduce a simple handover optimization. Handover decision is based on a speed of users and on a signal level. Extension of previous proposal is described in [58]. The paper proposes algorithm which modifies handover decision as well as management messages exchange. Proposed approach takes several parameters, such as QoS, required bandwidth, and a type of application into account. Authors define three states of mobility based on actual speed of users. For users moving with the speed of up to 15 km/h, the handover to the SCeNB is executed if the signal level of the target SCeNB exceeds signal level of the serving cell. If the user's speed is in range of 15 km/h and 30 km/h, the type of service is additionally assessed. Handover is executed only if the user is using real-time service. All other users who do not fulfill both above mentioned conditions cannot perform handover. The results of both papers show that the higher ratio of fast users lowers the signaling overhead for the proposed handover while the conventional algorithm increases the signaling overhead. Although the number of unnecessary handovers is reduced by this proposal, user's throughput is negatively influenced as well. The paper [59] focuses on efficient handover execution. In this approach, the QoS criteria for determining a target cell are introduced. The handover is performed in case if no mobility of user is detected and if an offloading of MeNB is necessary.

The idea of the previous papers is further elaborated in [60]. The handover decision is based also on an available bandwidth of the SCeNB and a category of the user. The UEs are categorized according to their membership in the CSG of HeNB. A user who is not included in the CSG is connected to the open/hybrid HeNB only if three conditions are fulfilled: i) the HeNB has available bandwidth, ii) the speed of user is lower than a threshold, and iii) the HeNB interferes significantly to the UE connected to the MeNB.

In [61], the authors also consider the speed of the user for the decision on handover. Unlike [58] and [60], the speed of users and the cell's configuration influence the setting of TTT parameter.

All these proposals are trying to restrict handover to the SCeNBs. However, these techniques are going directly against the main idea of deploying of SCeNBs. Their using leads to a reduction in utilization of the SCeNBs and the most of UEs stays connected to the MeNB. The suppression of a number of handover results to the fact that the capacity of SCeNBs is not fully exploited and the MeNB offloading by SCeNBs is limited. This MeNB can easily become overloaded since the SCeNBs interfere to the UEs connected to the MeNB. Hence, those UEs must consume more radio resources to reach required throughput. None of before mentioned methods considers fact that the connection via the SCeNB can be of a lower cost than the connection through the MeNB.

A proposal focused on the saving of users' expenditures and on offloading of the MeNB, is described in [62]. This proposal deals with the vertical handover between IEEE 802.16e WiMAX and Wireless Local Area Network (WLAN). The authors propose to deliver data belonging to delay-tolerant applications over the WLAN. As the result, there is a cost saving on the user's side. Nevertheless, the vertical handover to WLAN leads to significant handover interruption [63]. Moreover, QoS for voice services can be also impaired since QoS support in WLANs may not be implemented.

Contrary to above-mentioned proposals, which focus on reduction of number of handovers, the one of objectives of this thesis is to enhance handover decision by consideration of the cost of the connection via the SCeNBs and the MeNBs. Therefore, modifications of the conventional handover with the purpose to increase the time spent connected to the SCeNBs are presented. More time spent at the SCeNB is profitable from an operator as well as from the user's point of view. From the operator side, the advantage is to relieve existing network infrastructure. From the user's perspective, it enables to attain higher transmission rate and/or lower cost of the connection.

3.2 Neighbor Cell List management and scanning

With rising numbers of deployed SCeNBs in the network, a traditional manner of manual creation and maintenance of the NCL of MeNBs is no longer usable. Also the application of this manner for creation and maintenance of the NCL of SCeNBs is not possible.

Within a coverage area of one MeNB in the network with a dense deployment of SCeNBs, hundreds or thousands of SCeNBs may exist. Moreover by deploying of HeNBs, the central planning cannot be used since the owner of the SCeNB can place it anywhere and operator cannot influence the selection of position. Therefore, many of proposed principles for MeNBs cannot be used and the concept of Self-Organizing Network (SON) is introduced along with the next generation networks [63]. Due to this concept, creation and maintenance of the NCL of MeNBs and SCeNBs are performed automatically without the need for operator intervention.

The self-organizing NCL can be divided into two phases: self-configuration and self-optimization. In the self-configuration phase, suitable adjacent cells of a new deployed cell are selected. Thereafter, in self-optimization phase, this set of adjacent cells is continuously modified according to given requirements to ensure both minimum length of the NCL and minimum probability of a missing cell in the NCL.

To detect potential handover candidates, which are not present in the NCL during its creation (self-configuration phase), standardized algorithms denoted as Automatic Neighbor Relation (ANR) and Detected Set Reporting (DSR) are defined in LTE-A and WCDMA systems, respectively [63], [64]. By using these mechanisms, the UE needs not to know its neighboring cells before the scanning takes place since the UE can automatically scan only surrounding cells, which share the same frequency band as the serving cell [65], [66]. However, these standardized methods of finding suitable candidates for the handover bring a number of drawbacks. The major drawback of these mechanisms with respect to the future mobile networks considering carrier aggregation [67] or heterogeneity by means of multiple Radio Access Technology (RAT) consists in possibility of scanning only cells in the same band as the serving cell. It means the deployment of small cells in an orthogonal way, i.e., MeNBs and SCeNBs are not sharing the same bands, can lead to incomplete list of potential handover candidates. Efficient utilization of ANR or DSR is not possible in these networks since the inter-frequency or inter-RAT cell cannot be discovered. To ensure inter-frequency and inter-RAT scanning, the serving cell has to inform the UEs about the bands or frequencies where potential neighboring cells can be discovered. If the inter-frequency and inter-RAT cells are not scanned, the cells using different frequency band or different RAT can be underutilized as those are not known to the UEs and handover to those cells cannot be initiated. Consequently, other cells can become overloaded. Another shortcoming is particularly long scanning time, which can result in a drop in QoS or even drop of connection. As shown in [38], this algorithm is suitable only for searching for newly deployed cells (or neighboring cells of newly deployed cell) however not for the neighborhood scanning for handover purposes instead of using the NCL.

In the self-configuration phase, the NCL of MeNBs and SCeNBs can be derived essentially in two ways. The first one is denoted as sensing method and is used, for example, in [37]. The own scanning of newly added cell is essential idea of this proposal. The authors suggest the possibility of cells identification in neighborhood based on the received signal. The simulation results show how adjustment of the threshold value $SINR_{treshold}$ of the received signal affects the number of records in the NCL for different types of newly deployed cells and their adjacent cells (MeNBs and SCeNBs). If the threshold value $SINR_{treshold}$ is set too high, only cells from the immediate neighborhood with the highest SINR is chosen as members of the NCL. This brings a reduction of the overhead as cells that are not in the neighborhood are not included in the NCL. However, it may happen that a distant cells (and especially SCeNBs), which are also suitable candidates for the handover, are not included in the NCL. On the contrary, if the threshold value $SINR_{treshold}$ is set too low, large amount of cells which are not directly adjacent of the new cells are added to the NCL. It means the SCeNBs near to the new cell can be contained in the NCL even if the handover from the new cell to them is not possible as they are surrounded by other SCeNBs. It leads to increase of scanning overhead, prolong scanning procedure and increase energy consumption. In general, the sensing is very fast and simple, however, also very inaccurate and the number of cell in the NCL can easily exceed the maximum size of NCL (32 records [39]).

Another proposals focus on signal level measurement is presented in [68] and in [69]. In [68], the authors propose a method that automatically assigns NCL to the newly connected cells. The proposed solution assumes knowledge of exact cells' position. Three categories of algorithms are defined. The categories differ among others by complexity of antenna radiation approximation and thus in computational complexity and efficiency. In [69], the algorithm that considers empty NCL after initialization of a MeNB is described. Also geographical information on other cells and modeling of electromagnetic waves is used for estimation of coverage and NCL determination. However especially in case of HeNBs, the exact geographical coordinates are not known and could be changed depending on HeNB's owner at any time. Therefore in general, both ways cannot be used in network with SCeNBs since the position of HeNBs cannot be exactly determined. Therefore also the neighboring environment of HeNBs and also other type of cells cannot be efficiency reconstructed based on geographical information.

An extension of the sensing for purpose of MeNB is proposed in [70]. The authors propose to divide surrounding SCeNBs of the MeNB into sectors and tiers. Within each sector and tier, only a fraction of the total number of SCeNBs is contained. However, the paper does not mention, how to classify the SCeNBs to the layers and sectors. Moreover, determining the position of the UE based on the signal propagation from adjacent MeNBs is very inaccurate, especially indoor.

Sensing used by newly deployed SCeNBs bring another problem called hidden node problem. The problem consists in limited ability of discovering of all potential candidates for handover and it is caused due to an obstacle (e.g., wall) between SCeNBs. This problem is addressed, for example, in [35], [71]. The paper [35] addresses the creation and maintenance of the NCL in SCeNBs. The basic premise of the proposed mechanism is that the cells are within mutual range. The proposed method determines the approximate location of the SCeNBs based on the level of received signal from all neighboring SCeNBs. Collocation of the SCeNBs can be reconstructed based on knowledge of approximate position. Hidden neighborhoods can be detected on the basis of the calculated position. The disadvantage of the proposed procedure is the assumption on ability of SCeNB to receive signals from neighboring SCeNBs. As the radius of SCeNBs is low, the fulfillment of this assumption is unlikely and cannot be ensured all the time in real networks. Therefore the utilization of this algorithm is limited.

Second essential way, how to determine the neighboring cells, is based on a handover history [72], [73], [74]. This approach exploits monitoring of the handover performed by the UEs in the past. This approach is developed for networks with MeNBs. However, it can be easily extended to the SCeNB networks. Beside the frequencies corresponding to all known neighbors included in the NCL, the testing NCL have to contain also one or more randomly selected testing frequencies for searching new neighbors. This allows scanning the frequencies of MeNBs and SCeNBs that are nearby, but not yet in the NCL. Testing frequencies are changed for each scanning to enable scanning whole available band. If a signal received at the test frequency is evaluated as strong enough, corresponding cell is added to the NCL as a new member. Ideal length of NCL depends on the model of network infrastructure as can be observed from simulation results. The results also show that the algorithm is able to adapt to changes in the network after roughly five hundred handovers performed in a given cell. Moreover, the speed of adaptation is highly dependent on the network model, network load, and measurement capabilities of UE. In comparison with the sensing, the handover history is more time consuming, however, it is also much more accurate, since only cells to which some handovers are performed are kept in the NCL. To create a usable NCL, it is necessary to carry out a sufficient number of handovers that could be performed to identify all neighboring cells.

A specific way to speed up the handover scanning process is represented by a cache scheme presented in [75]. The authors propose to use a cache to store the cell information of the recently visited SCeNBs and used it to speed up the process when the EU returns back to the SCeNB-tier. Then, the UE scans only SCeNBs included in cache instead of scanning all SCeNBs in the NCL. The cache scheme exploits the Wireless Mobility Management (WMM) location based approach using UE's location information for routing data for UE, as introduces in [76]. The overall size of used cache is related to the amount of cells accommodated the same frequency band.

An improvement of handover history is a scheme based on Radio-Frequency Fingerprints (RFFs). This method is investigated in [77], [78] and in [79]. By using this scheme, the UEs need to access a database with RFFs. On the basis of the RFF and measurement performed by the previously passed UE, an approximate position of the UE can determined. According to the observed position, potential handover candidates can be identified and scanned. This approach shows improvement in performance comparing to other approaches. However, its efficiency can be heavily impaired if deployment of cells or a channel quality are changed. It also implies high overhead due to a need for frequent exchange of the RFFs between location of the database and the UE if the database is deployed in the core network. If the database is deployed in the UE, then demands on the UE in terms of database storage rises significantly [80]. Especially in the network with small cells, the volume of transferred and stored information is enormous and it can result in a reduction of QoS.

Approximate position and distance between the UE and HeNBs is used in mechanism called Autonomous Search Function (ASF) [39], [81]. However, the scanning by using ASF is performed based on previously visited CSG member cells in white list. Therefore, the ASF is applicable for the closed and the hybrid HeNBs only and it cannot be used for general SCeNBs or HeNBs with the open access.

Although the cells in the NCL created by the handover history are already actual neighboring cells, their number could be still excessive especially in case of NCL of MeNBs in the network with SCeNBs. Therefore, an inclusion of all these cells is not possible since the scanning procedure is not efficient and can result in a decrease in QoS and rising of energy consumption due to the unnecessary scanning and the selection of appropriate handover candidate is delayed. Thus, in case of the NCL of MeNBs, the self-optimization, which follows after the self-configuration, is represented especially by a reduction of the number of cells in the NCL.

In the most of cases, the number of neighbors is reduced based on statistical frequency of handovers performed to individual neighboring cells [73], [82], [83] or based on the length of the NCL [84]. In paper [83], the neighbor cells are eliminated from NCL if no handover to the cells is performed during certain period. Another approach is presented in [85], where the NCL is adjusted based on the traffic load of the cell.

An algorithm for dynamic adjustment of the NCL is described in [36]. The authors propose two algorithms for the efficient NCL maintained on the basis of statistical evaluation of user's movement. The results show that the using of both algorithms enables the reduction of amount of items in NCL comparing to the standard approach of creating NCL. The proposed algorithm could be used mainly in MeNBs that cover a large number of SCeNBs. On the other hand, any elimination of a neighbor to which the handover can be performed leads to a rise in probability of missing handover target cell and consequently to the call drops. This is the critical issue especially during the movement in the network with the SCeNBs as their signal fluctuates rapidly.

For efficient energy consumption, the scanning process can be performed frequently only if RSRP of the serving cell is at a low level as described in 3GPP standard ([39] and [86]). However SCeNBs can be deployed also in areas with sufficient RSRP of MeNB. Therefore, usage of this scheme would lead to the situation when the SCeNBs are not discovered. Consequently, main motivation for deployment of the SCeNBs, i.e., offloading of the MeNB and providing higher throughput to the UEs, is suppressed. Note that the simple solution by means of lowering the RSRP level for scanning of SCeNBs would lead to redundant scanning and to consequent rise in energy consumption.

Another way of reduction of energy consumption is to take a mobility state of the UE into account. This possibility is investigated, for example, in [87] or [88]. According to [39], the mobility state is estimated based on the number of handovers performed within a specified time window. It enables to distinguish three mobility states: normal, medium, and high. Based on mobility state, the frequency of scanning is derived [89], [90].

Another scanning algorithm is presented in [89] and proposed for 3GPP standard in [91]. The scheme is denoted as Background Inter-frequency Measurement (BIM) and it performs the scanning during the entire movement of the UE within area of the MeNB. To reduce amount of scanning events, the period for MeNB scanning is prolonged. This modification ensures lower power consumption and also keeps the possibility of finding a suitable SCeNBs for handover even if the RSRP of MeNB is sufficient. However, the proposed algorithm does not take into account impact of the density of SCeNBs on the optimum scanning period. It means the scanning period suitable for one MeNB with a given density of SCeNBs can lead to ignorance of SCeNBs or to redundant scanning in another MeNB. Modification of the scanning interval of individual cells is exploited also in [92]. The authors suggest to select scanned cells according to the probability of handover to the given cell and SINR observed by the UE from its serving cell. In means, more frequent handover targets are scanned more often than other cells. This leads to a significant reduction of the number of scanned cells while call drop rate is not impaired. However, like in the previous papers, the authors do not consider utilization of the SCeNBs and potential overloading of the MeNBs.

The main contribution of this thesis consists in proposals dealing with efficient creation of NCL of new installed SCeNBs and creation of NCL of new deployed MeNBs if underlying SCeNBs are deployed. The created NCL contains only the neighboring cells, which are accessible from the actual location of the user. Proposal of NCL for MeNBs is further extended by efficient neighborhood scanning algorithm. Proposed algorithm focuses on minimization of the number of scanned cells and, therefore, on reduction of energy consumption of the UEs due to scanning if the UE is attached to the MeNB. At the same time, proposed algorithm enables high utilization of the SCeNBs to maximize throughput of the UEs. With respect to above mentioned papers, proposed approach reflects real speed of UEs as well as the relative position of UE in the network and aims on the efficient scanning process ensuring the best possible QoS while energy consumption of UEs due to scanning is minimized. The performance gain of proposed approach is achieved by usage of the knowledge of previously visited cell, the principle of obstructed paths, and estimation of time of transition between cells.

4. Methodology and scenarios for performance evaluation

This Chapter defines deployments and scenarios used for particular evaluation of proposed approaches. The first section describes models used for improving of utilization of SCeNBs' communication resources. In the second section, models exploited for creation of the NCL of new deployed SCeNB and for creation of the NCL of new deployed MeNB in network with the SCeNBs are introduced. Furthermore, new proposed mobility model with Points of Interests (PoIs) respecting real behavior of users in a city is described in this Chapter. Last section describes model used for evaluation of proposed algorithm for selection of SCeNBs exploited computational resources of SCeNBs.

4.1 Extension of time spent by users in SCeNBs

For proposal focused on maximally exploitation of communication resources of SCeNBs, an area with twenty-five blocks of flats with square shape is used for simulation of users' movement. The blocks of flat are arranged with size of 5 x 5 blocks according Figure 6. Size of each block is 100 x 100 meters and contains 64 apartments with size of 10 x 10 meters. The apartments are located in two rows around the perimeter. Blocks are separated by streets with the width of 10 meters. Three SCeNBs are deployed per a block. Each SCeNB is placed in random position in random flat for each drop. The MeNB is located in distance of approximately 50 meters from the closest block in the right top corner of the simulation area.

Thirty users move along the streets according to Manhattan mobility model. The speed of each user is 1 m/s. Each UE passes 3000 m during the simulation. Indoor users are not included in simulation as sufficient coverage of a flat by SCeNBs signal is assumed and thus a movement within the flat does not cause handover.

The quality of signal received by the UE from the SCeNBs is determined according to ITU-R P.1238 path loss model [93]. The signal between UE and the MeNBs is derived by Okumura-Hata for outdoor to outdoor communication [94]. Wall losses are considered for both models.

In the simulations, the proposed modified handover decision is evaluated and compared with three algorithms: algorithm based on comparison of Carrier to Interference and Noise Ratio denoted as CINR, algorithm based on comparison of Received Signal Strength Indication (RSSI) and Moon's algorithm.

The algorithm denoted as CINR is a conventional handover decision based on comparison of CINR levels of a serving cell and a target cell. The handover is performed, if the CINR level of the target cell is higher than the CINR level of the serving cell with additional Δ_{HM} according (1). The RSSI based algorithm is analogical to the conventional CINR based handover according (1). However, instead of CINR, the decision is based on comparison of the RSSI levels. The algorithm denoted as Moon is proposed in [55] and further specified in [56]. According to this algorithm, the handover is initiated based on a combination of the received signal levels from the serving MeNB and the target SCeNB. The level of the received signal from the SCeNB is compared with the absolute threshold level of –72 dB. Moreover, the signal level of the MeNB is confronted with a combination of the signal levels from the MeNB and the SCeNB. The handover to the SCeNB is performed if the SCeNB offers signal level above the threshold and simultaneously the SCeNB is deployed at sufficient distance from the MeNB. If the conditions are not fulfilled the handover is performed according to the conventional handover scheme.

For the evaluation of the handover outage probability and the overall outage probability, a CINR Outage Limit ($CINR_{OL}$) is defined. It is the level of the CINR, under which the QoS is not fully guaranteed. It means the transmission speed and quality of the user's channel are very low. According to [95] and [96], the $CINR_{OL}$ is set to *–3 dB*. The major simulation parameters are summarized in Table 1.

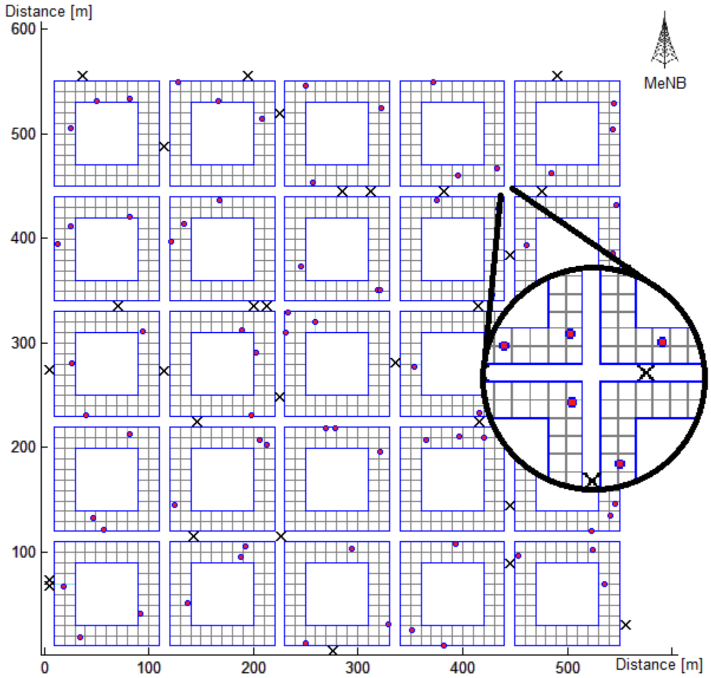


Figure 6: Example of random deployment for maximization of SCeNBs utilization

Parameter	**Value**
Frequency [GHz]	2
Channel bandwidth [MHz]	20
Transmitting power of MeNB / SCeNB [dBm]	46 / 15
Height of MeNB / SCeNB / UE [m]	32 / 1 / 1.5
External / internal wall loss [dBm]	10 / 5
$CINR_{OL}$ [dB]	–3
$CINR_{T,in}$ [dB]	–3
Simulation real-time [s]	3 000

Table 1: Parameters of simulation for maximization of SCeNBs utilization

4.2 Neighbor Cell List and scanning

In this section, first model for creation of NCL of newly installed SCeNBs is introduced. Later, the simulation environment exploited for creation of NCL of MeNBs and also for scanning of neighborhood by UE is described.

4.2.1 Creation of NCL of new installed SCeNBs

The evaluation of the proposed method is done for SCeNBs (represented by HeNBs in the open access) regularly deployed in houses along both sides of the street (boulevard) with 30 m width and 100 m length (length of the street was adjusted by the number of SCeNB during the measurement of delay). Each of houses contains one SCeNB. The vertical and horizontal distance between SCeNBs is 20 m and 45 m, respectively. The MeNB is placed in distance of 500 m from the middle of the street.

The user walks on the street and counts the number of handovers and the number of the new record to NCL is stored. The user can move to the sidewalk on the both side of the street. The width of the sidewalks is 2 m. User can cross the street once per passing the street on the random place. The selection of random place for crossing the street is uniformly distributed. The speed of user is 1 m/s.

The signal quality from SCeNB is evaluated according to the ITU-R P.1238 path loss model for one floor house including wall losses [93]. The Okumura-Hata path loss model for outdoor to outdoor communication [94] is used for determination of MeNB's signal propagation. Simulation parameters are summarized in Table 2.

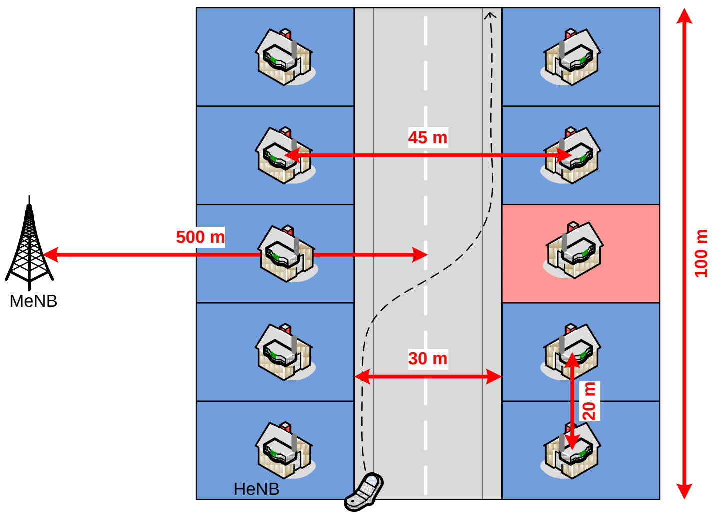


Figure 7: Simulation deployment for creation of SCeNBs' NCL

Parameter	Value
Street Width / Length [m]	30 / 100
Number of MeNB / SCeNBs	1 / 10

MeNB Dist X [m]	500
SCeNBs Dist X / SCeNBs Dist Y [m]	45 / 20
Height of macro MeNB / SCeNBs / UE [m]	32 / 1 / 1.5
Frequency [GHz]	2
Channel bandwidth [MHz]	20
Transmitting power of MeNB / SCeNBs [dBm]	43 / 15
External Wall Loss [dB]	15

Table 2: Parameters of simulation used for creation of SCeNBs' NCL

The new SCeNB can be placed anywhere without requirement on detection of the signal from its neighbor SCeNBs, only signal from MeNB is received. On the site of operator, the database of temporary coarse location determined based on the signal received from MeNBs of all connected SCeNB is required.

4.2.2 Advanced mobility model with POIs for creation of NCL of MeNBs and for distance based-scanning

For the evaluation of self-organizing NCL of MeNBs and distance-based scanning process, a part of Prague, Czech Republic is considered. The simulated area is depicted in Figure 8. The area consists of four horizontal and five vertical streets surrounding flats, offices, shops, and restaurants. Neighboring buildings are of five floors height. Within this area, four eNBs (represented by microcells) are deployed according to the real deployment of Vodafone mobile operator. The simulations are performed for various densities of SCeNBs (represented by HeNBs in the open access). The SCeNBs are dropped randomly into flats, shops, restaurants, offices, or working areas as shown in Figure 8. If a SCeNB is placed to a flat, the floor is randomly selected from one to five with equal probability.

Figure 8: Simulation area in Prague, Czech Republic with position of microcells (blue circles), SCeNBs (orange crosses), and streets (red lines)

Signal propagation from the base stations to the UEs is derived according to models recommended by Small Cells Forum. As in the previous cases, it means Okumura-Hata [94] and ITU-R P.1238 [93] models are used for the signal propagation from MeNBs and SCeNBs, respectively.

The duration of a simulation is 500 000 s of real-time. Out of this period, first 100 000 s is a monitoring period used for collection of the handover statistics. This interval is not included in the results. The results are derived from consecutive 400 000 s following the monitoring period. The duration of the monitoring period is set according to the time required by all proposals to collect enough parameters to derive the NCLs for all cells. The results are averaged out over ten simulation drops for each algorithm and for each density of SCeNBs.

Transmission characteristics and other simulation parameters are summarized in Table 3.

Parameter	**Value**
Carrier frequency [GHz]	2
Transmitting power of MeNB / SCeNB [dBm]	27 / 15
Height of MeNBs / SCeNBs / UEs [m]	32 / {1.5 + 3×(floor−1)} / 1.5
Number of MeNBs / SCeNBs / UEs	4/ {0 −200} / 100
Attenuation of walls [dB]	10
Hysteresis for handover [dB]	4
Threshold for pruning, T_p [%]	1 [82]/ 5
Energy consumption per scanned cell, ρ [mWs]	3 [89]
Default scanning period, Δt [s]	1
Default Guard Interval, *GI* [s]	1
Hysteresis for handover [dB]	4
Total time of simulation, T_{SIM} [s]	500 000
Monitoring period [s]	100 000
Number of simulation drops	10

Table 3: Simulation parameters used for self-organizing NCL of MeNB and scanning of neighborhood by UE

For real simulation of movement of users in urban areas, the new mobility model with POIs is developed. The mobility model is based on Manhattan mobility model supplemented with POIs. The model exploits graph theory approach for finding the shortest possible path between two POIs [97].

There are 100 UEs moving in the simulation area. All users move in the middle of sidewalks. A width of the sidewalk is 2 m and a width of streets is equal to 16 m (including sidewalks). The distribution of user’s speed as well as the distribution of acceleration is normal with mean value 1.127 m/s [98]. Estimation of users’ speed is performed based on [99] and [100]. According to the [100], maximum estimation error of 2 % is assumed in general scenario but also investigation of the impact of estimation error beyond this limit is made. Based on the maximum speed of users in simulation and based on [91], the default scanning period Δt is set to 1 second. Default value of Guard Interval (*GI*) used for proposed algorithm is set to 1 second (as stated in Table 3).

Each user may cross the street only at intersections. For purposes of this simulation, a time relation of the UEs' movement is not needed to know. Therefore, users moving without stops are considered. Hence, once a UE reaches its destination, it chooses another destination and starts moving again. This way, the situations when a UE stays at the same place for a long time are eliminated. If the UE is not moving, an impact on the NCL is negligible as the UE stays fixed typically indoor where the NCL is influenced by signal level fluctuation only marginally due to wall attenuation.

In the simulation area, following POIs are considered: two office buildings, two restaurants, two shops, and ten blocks of flats. The intersections at which the users enter and leave the simulation area are also understood as the POIs. Individual users move between these POIs and always select the shortest path. The probability that a user visits a POI is derived from the behavior of users in the area. The position of all POIs follows the real situation in the simulated area.

Based on the observation, four types of users are classified. The first set of users represents people who live outside the simulation area but work inside of it. For these users (denoted as "workers"), a place of employment is randomly determined. This location can be an office building (with a probability of 40 % per office building), a restaurant (5 % per restaurant), or a shop (5 % per shop). All workers arrive to the working place from outside the simulation area. Therefore, an intersection at the edge of the simulation area is selected as a point of entering and exiting the area. Besides moving between the work place and enter/exit of the area, the worker can also visit other POIs with a certain probability. On the route to work, the worker can visit a shop with probability of 5 % per shop. On the way home, this user can visit a shop (10 % per shop) or a restaurant (10 % per restaurant). An example of a movement of a worker is depicted in Figure 9a.

The second type of user is a "resident". When compared to the worker, the resident lives in the simulation area and works outside. To that end, one of the POI is the place of residence (flat) and the second POI corresponds to the intersection where the resident leaves and enters the simulation area (see Figure 9b). Similarly as the worker, the resident can visit other places. On the way home, the resident can visit a shop (probability of 10 % per shop) or a restaurant (10 % per restaurant). After coming home, the resident can visit a shop (15 % per shop) or a restaurant (15 % per shop). From there, the resident user always goes back to home. Note that the resident can also stay home and go directly to work visiting neither restaurant nor shop (probability of 50 %). In this case, the next movement of the resident is towards the point where he/she leaves the area.

The third set of users is called a "visitor". These users enter the simulation area at a random intersection and visit an office building (probability of 2.5 % per building), a shop (12.5 % per shop), a restaurant (12.5 % per restaurant), a block of flats (2 % per block), or they just pass through the area without any stop (25 %). After visiting certain POI, the visitor leaves the area again at one of the randomly selected intersection (see Figure 9c).

The last set of users is so called a "roaming resident". Their movement through the simulation area may reflect the behavior of people walking with dogs or strolling people. The movement follows conventional Manhattan mobility model with no modification (see Figure 9d). These users do not leave the simulation area at all and have only one POI, which represents their home. The roaming resident starts walk always at home. The length and direction of each walk is generated randomly. After the walk is over he/she returns back to home. This cycle is continuously repeated during the simulation.

All important parameters of proposed mobility model are summarized in Table 4.

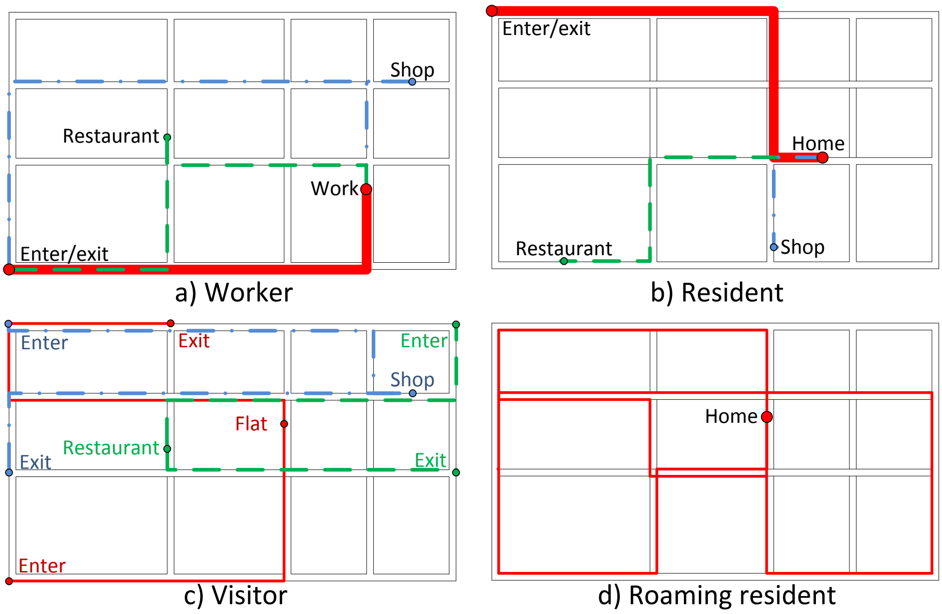


Figure 9: Example of movement of users in the simulated area. Thickness of a line is proportional to the frequency of movement of a UE in the street

Parameter	Value
Number of users in simulation	100
Ratio of workers [%]	30
Ratio of residents [%]	40
Ratio of visitors [%]	20
Ratio of roaming residents [%]	10
Mean speed of users [m/s]	1.127 [98]
Standard deviation of speed [m/s]	0.5324 [98]
Mean acceleration [m/s^2]	0.0004 [98]
Standard deviation of acceleration [m/s^2]	0.2175 [98]
Default accuracy of speed estimation [%]	2 [100]
Number of office buildings	2
Number of restaurants	2
Number of shops	2
Number of blocks of flats	10

Table 4: Parameters of advanced mobility model with POIs

4.3 Exploitation of computational resources of SCeNBs

One cluster in the SCC network is used as the simulation environment. This cluster is composed of 500 UEs connected to 50 SCeNBces managed by one SCM. The UEs are distributed among individual SCeNBces randomly with uniform distribution. Each UE is connected to the serving SCeNBce via LTE-A mobile network. The SCeNBce is further connected to the operator's core network through Asymmetric Digital Subscriber Line (ADSL) or optical fiber Gigabit Passive Optical Network (GPON) backhaul. Models of both backhauls are based on real measurements carried out by operator TELKOM Indonesia in real network [46]. Distribution functions and their parameters for backhaul modeling are listed in Table 5.

Type of backhaul	**Direction**	**Distribution function**	**Parameters**
ADSL	Upload	Generalized Extreme Value	k = 0.72894 σ = 0.01717 μ = 0.0068
	Download	Burr	α = 680.84 c = 4.8501 k = 0.32447
GPON	Upload	Generalized Extreme Value	k = -0.35212 σ = 335.92 μ = 747.8
	Download	Generalized Extreme Value	k = 0.78459 σ = 0.82368 μ = 0.43375

Table 5: Backhaul modeling [46]

The simulation time is 2 000 seconds. The first half of this time (i.e., 1 000 seconds), is denoted as incoming period. During the incoming period, each UE generates from 1 to 20 offloading requests. All requests are uniformly distributed along whole incoming period. With 500 UEs in the scenario, from 0.5 to 10 requests in average come to the cluster every second during the incoming period. The SCM handles incoming requests by means of First In First Out (FIFO). The assumption that all requests are considered to be offloaded to the SCC is made. The processing of the tasks by the SCeNBce is performed in FIFO order as well.

Requests for offloading correspond to the applications listed in Table 6. The probability of occurrence of each application is the same for all of them (i.e., 20 % for each application). Parameters of each application are generated randomly with normal distribution with mean value set according to Table 6. Standard deviation, σ, is equal to 1/10 of the mean value. General system parameters and simulation configuration are summarized in Table 7.

Application	**Mean size of tasks R_{U-S} [MB]**	**Number of instructions M [-]**	**Required handling time Ψ [s]**	**Mean size of results R_{S-U} [B]**
Face	8.3	$3.664 \cdot 10^6$	37.0	60
Speech	64.8	$5.445 \cdot 10^6$	63.0	50
Object	39.5	$23.289 \cdot 10^6$	62.8	50
Augmented reality	97.5	$0.931 \cdot 10^6$	140.2	20
Fluid	0.5	$0.508 \cdot 10^6$	7.3	25

Table 6: Parameters of requests [101]

Parameter	**Value**
Incoming period [s]	1 000
Total time of simulation [s]	2 000
Total number of requests/tasks coming to the cluster during incoming period	500 – 10 000
Number of UEs generating requests/tasks	500
Number of SCeNBces in cluster	50
Average maximum computing power of SCeNBce, P	10^6
Number of simulation drops	100

Table 7: Simulation parameters of SCC

5. Extension of time spent by users in SCeNBs

The conventional handover decision is based on comparison of the signal level of the target ($\overline{s_t}[k]$) and serving ($\overline{s_s}[k]$) cells, as mentioned in (1). Commonly, a Δ_{HM} can be used in order to mitigate a ping-pong effect (i.e., frequent handover between two neighboring cells). To additional elimination of redundant handovers, a timer (e.g. TTT [102]) can be implemented. The conventional handover algorithm is designed for networks with MeNBs only and does not consider specifics of heterogeneous network composed of both MeNBs and SCeNBs. However their usage in network with SCeNBs leads to underutilization and to wasting of capacity of the SCeNBs. Therefore, the conventional handover algorithms should be modified to maximize the time spent by users in the SCeNBs and, consequently, to either offload MeNBs or reduce the connection cost if the SCeNBs provides lower connection cost than the MeNBs.

This Chapter first describes two proposals of handover decision for maximization of the time in SCeNBs: modification of hand-out hysteresis and modification of hand-out threshold level. In the following sections, impact of the proposed methods on prolongation of time spent by users connected to the SCeNBs and outage probability are evaluated. The third section focuses on determination of an optimum hand-out threshold level by consideration of the connection cost based on the requirements of users.

5.1 Maximization of time in SCeNBs by hand-out hysteresis

At first, the approach maximizing the time spent by the users connected to the SCeNB is described. The extension of the time in SCeNB is achieved by prolongation of hand-out hysteresis. This approach is presented and evaluated in following subsections.

5.1.1 Maximization of time in SCeNBs by modification of hand-out hysteresis

Prolongation of the time spent in the SCeNBs allows offloading of neighboring MeNBs. On the other hand, the long stay in the SCeNB if the UE is moving out of the SCeNB's coverage area can cause a degradation of quality of user's connection. Therefore, the possibility of prolongation of the time spent in the SCeNB by the user (t_{SCeNB}) is investigated in this section. First, an extension of the t_{SCeNB} is adjusted by the hand-out hysteresis used if the user is leaving the SCeNB.

When a user is moving from a MeNB to a SCeNB or from one SCeNB to another SCeNB, no hysteresis is considered since this hysteresis shortens the t_{SCeNB}. Handover is performed immediately after the monitored parameter of the target SCeNB exceeds the same parameter of the serving MeNB and if the target SCeNB can offer sufficient QoS to serve the UE. This mechanism further prolongs the t_{SCeNB}. The early handover might lead to significant degradation of the QoS, an increase in the outage probability, or an increase in the number of redundant handovers due to selection of inappropriate target cell. Exclusion of the hysteresis could increase amount of redundant handovers due to ping-pong effect. Therefore, a one-second long timer TTT between two handovers is considered. When the handover between two MeNBs is performed, the level of hysteresis is set according to the conventional MeNB network criteria. The principle of the handover decision for prolongation of t_{SCeNB} is depicted in Figure 10.

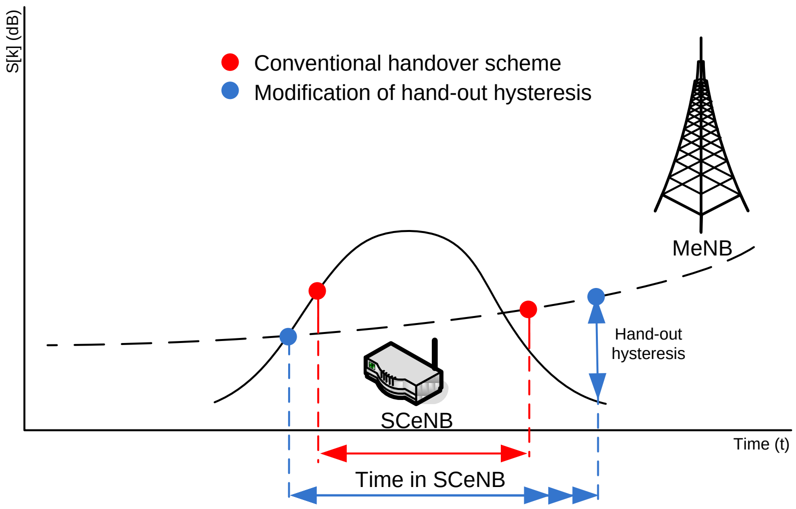


Figure 10: Handover decision for maximization of the time in SCeNB by hand-out hysteresis

5.1.2 Evaluation of impact of hand-out hysteresis on time in SCeNB

As mentioned in section 4.1, the evaluation of impact of hand-out hysteresis is performed for algorithms based on CINR, RSSI and for Moon’s algorithm. As can be seen in Figure 11, the t_{SCeNB} rises almost linearly with the hand-out hysteresis for all three handover strategies. The steepest rise is observed for the handover based on RSSI. The growth is approximately 1.9 s/dB. For no hand-out hysteresis, the similar result is achieved also by CINR based handover. However, the rise in t_{SCeNB} is roughly 1.25 s/dB for the CINR based handover. The shortest time spent by the UE in the SCeNB is reached by the Moon’s algorithm. For no hand-out hysteresis and Moon’s algorithm, the t_{SCeNB} is significantly shorter than for another two handovers (25.2 s). The t_{SCeNB} for Moon rises with 1.35 s/dB. Dependence of the t_{SCeNB} on the hand-out hysteresis can be expressed by using the formula for a straight line:

$$t_{SCeNB}(\Delta_{HM}) = t_{SCeNB}(\Delta_{HM} = 0) + tp \cdot \Delta_{HM} \quad (4)$$

where Δ_{HM} is the hand-out hysteresis and *tp* is the time prolongation in s/dB. The *tp* is 1.9 s/dB, 1.25 s/dB, and 1.35 s/dB for RSSI, CINR and Moon's handover, respectively. Then the equations for all three algorithms are as follows:

$$t_{SCeNB,RSSI}(\Delta_{HM}) = 32.6 + 1.9 \cdot \Delta_{HM} \quad (5)$$

$$t_{SCeNB,CINR}(\Delta_{HM}) = 32.1 + 1.25 \cdot \Delta_{HM} \quad (6)$$

$$t_{SCeNB,Moon}(\Delta_{HM}) = 25.2 + 1.35 \cdot \Delta_{HM} \quad (7)$$

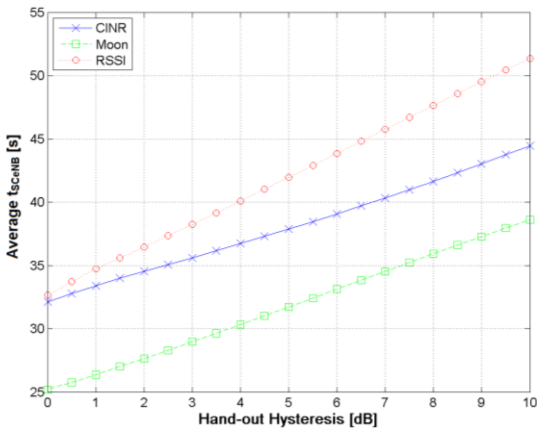


Figure 11: Average time spent in the SCeNB over hand-out hysteresis

Higher hand-out hysteresis and increase in t_{SCeNB} lead to a degradation of the received signal quality due to decreasing level of the SCeNB's signal and increasing interference from cells in the UE's vicinity. It may results in a lower quality of service or drop of the connection especially for UEs close to the cell edge. The quality of service can be represented by an outage probability. The outage probability is understood as the ratio of t_{SCeNB} when the CINR level of the SCeNB is under an outage limit to the overall time of the simulation run. The outage limit, denoted as $CINR_{OL}$, is the level of CINR, under which the transmission rate and the quality of user's channel is not fully guaranteed, as mentioned in section 4.1. According to [95] and [96], the $CINR_{OL}$ is set to *–3 dB.*

The average outage probability over hand-out hysteresis for all three handover algorithms is depicted in Figure 12. As the figure shows, the highest outage probability for each level of hand-out hysteresis is reached by the Moon's algorithm. The outage probability is roughly 2.2 % for no hand-out hysteresis if Moon's algorithm is used. The outage probability for no hand-out hysteresis and for both CINR and RSSI based algorithms is approximately 0.2 % and 0.8 %, respectively. The outage probability rises the most rapidly for the Moon's algorithm. For hand-out hysteresis of 10 dB, the outage for Moon's algorithm is roughly 26.5 % while only 5 % and 14 % outage is observed for CINR and RSSI based handovers, respectively.

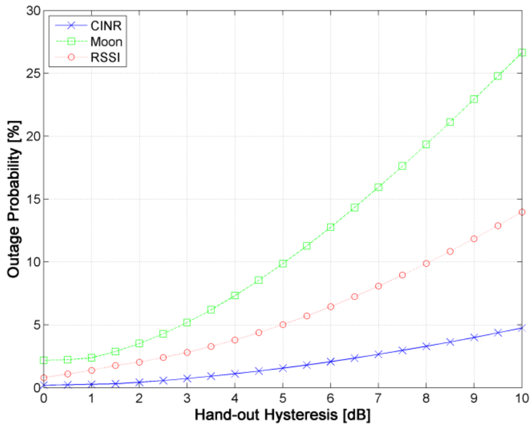


Figure 12: Outage probability of UE over hand-out hysteresis

From the comparison of all three handover algorithms can be seen that Moon's algorithm shows the lowest average t_{SCeNB} and highest outage probability in comparison with conventional CINR and RSSI based algorithms. The handover algorithms based on CINR and based on RSSI show better results in outage probability and in the average t_{SCeNB}, respectively. For CINR and RSSI based handovers, there is a trade-off between t_{SCeNB} and outage. However, since CINR based handover shows lower outage probability, it is used for modification in approach presented in following section.

5.2 Maximization of time in SCeNBs by hand-out threshold level

In this section, further prolongation of time in SCeNBs is presented. In the first subsection, the proposed modification of hand-out hysteresis in order to prolong the time spent by UE connected to the SCeNBs is presented. In second subsection, the evaluation of proposed algorithm is provided.

5.2.1 Maximization of time in SCeNBs by modification of hand-out threshold level

In the previous section, the proposed extension of the handover decision was based on absolute levels of the CINR. In this section, the decision is extended and a trend of the SCeNB's CINR level (as shown in Figure 13), and the acceptable outage for users are taken into account. The modified algorithm compares the CINR values rather than RSSI since the interference significantly influences a quality of a radio channel. Hence, CINR shows lower outage probability with rising of hand-out level (as shown in Figure 12). Due to consideration of the CINR based handover decision, the SCeNB is accessed more effectively at a time when it is able to provide higher throughput.

The proposed handover to the SCeNB (hand-in) is performed immediately when the CINR level of the SCeNB (denoted as $\overline{s_{SCeNB}}[k]$) exceeds a threshold $CINR_{T,in}$ as expressed in (8). The $CINR_{T,in}$ is set as a fixed value equal to the minimum level of CINR when the UE can be served by the SCeNB as shown in Table 1. In addition to (8), the level of the signal received from the SCeNB must be rising as well (see (9)). The requirements on the rising signal level provides a certain level of a prediction. Thus, it can be assumed that the user is moving in a direction to become closer to the SCeNB. This way, the ping-pong effect is suppressed, the time spent by users in the SCeNB is maximized, and the UE's outage is not increased.

$$\overline{s_{SCeNB}}[k] > CINR_{T,in} \tag{8}$$

$$\overline{s_{SCeNB}}[k-1] < \overline{s_{SCeNB}}[k] \tag{9}$$

when the UE is leaving the SCeNB, the handover is initiated according to the absolute CINR level of the SCeNB as well. Moreover, the trend of the SCeNB's CINR level and the actual level of the MeNB's CINR are also taken into account. The handover from the SCeNB to the MeNB is performed only if the following conditions are fulfilled: i) the CINR level from the SCeNB is lower than the level $CINR_{T,out}$ as defined in (10); ii) the CINR level of the MeNB ($\overline{s_{MeNB}}[k]$) exceeds the CINR level of the SCeNB (see (11)); and iii) the trend of the signal received from the SCeNB is declining, as expressed in (12).

$$\overline{s_{SCeNB}}[k] < CINR_{T,out} \tag{10}$$

$$\overline{s_{SCeNB}}[k] < \overline{s_{MeNB}}[k] \tag{11}$$

$$\overline{s_{SCeNB}}[k-1] > \overline{s_{SCeNB}}[k] \tag{12}$$

The handover between two SCeNBs is performed based on the same conditions as in the conventional algorithm (defined in (1)).

To avoid an immediate handover back to the MeNB a short timer is considered. During this timer no backward handover can be performed. The imminent handover might occur if the value of $CINR_{T,in}$ is set lower than the value of a threshold for handover from the SCeNB ($CINR_{T,out}$).

As depicted in Figure 13, the proposed approach leads to earlier initiation of the handover to the SCeNB comparing to the conventional handover. Contrary, the connection to the SCeNB remains for a longer time then in the conventional approach if the user is leaving the SCeNB. This is since the UE performs the handover only if the SCeNB is no longer able to satisfy QoS requirements of the UE. Therefore, the threshold $CINR_{T,out}$ must be related to the QoS required by individual UEs. In this section, the QoS requirements are represented by an outage probability. The outage probability is expressed as the probability of being in a state when the user cannot transmit data. However, other metrics can be implemented and considered in the same way.

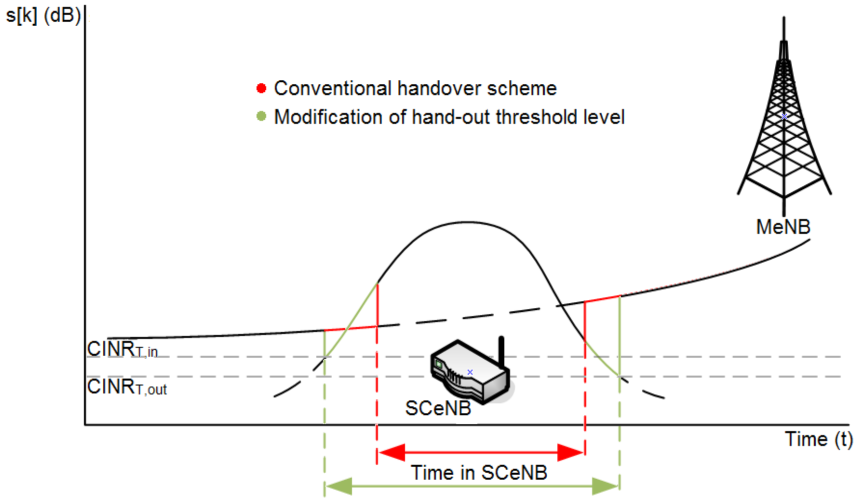


Figure 13: Handover decision for maximization of the time in SCeNB by hand-out threshold level

An optimum $CINR_{T,out}$ should be determined with respect to the user's preferences in either cost of the connection or the quality of the connection. The variable threshold $CINR_{T,out}$ enables a consideration of different cost of the connection via the MeNB and the SCeNB. If a user can tolerate lower quality of the connection, it can spent more time connected to the SCeNBs. Then, an operator benefits from lower load of the MeNB. Therefore, the operator can give a benefit, such as discount on cost of services, if the user would accept to stay connected to the SCeNB for a longer time even if it would lead to minor drop in quality.

5.2.2 Evaluation of impact of hand-out threshold level on time in SCeNB

The evaluation of impact of hand-out threshold level is made for three observed and compared parameters: t_{SCeNB}, outage probability, and handover outage probability. As in previous case, the evaluation of impact of hand-out threshold level is performed for algorithms based on CINR, RSSI and for Moon's algorithm which are described in section 4.1. These three algorithms are simulated for two levels of hysteresis, i.e., Δ_{HM} = 1 dB and Δ_{HM} = 4 dB.

The time spent in the SCeNB denoted as t_{SCeNB} is understood as the average duration of the connection of the UE to the SCeNB. In other words, it is an average time interval between the handover to the SCeNB and the handover back to the MeNB.

The results of evaluation of t_{SCeNB} over $CINR_{T,out}$, presented in Figure 14, show that t_{SCeNB} is rising with decreasing level of $CINR_{T,out}$ for the proposed handover. Comparing to the other competitive algorithms, proposed modification of handover outperforms the Moon's algorithm for all levels of $CINR_{T,out}$. Note that t_{SCeNB} reached by the Moon's algorithm is nearly independent on hysteresis. Performing handover based on the CINR levels leads to a prolongation of t_{SCeNB} with increasing hysteresis. However, even for the hysteresis of 4 dB, the proposed scheme achieves higher t_{SCeNB} if $CINR_{T,out}$ < –3.4 dB. The improvement in t_{SCeNB} can be reached by the replacement of the conventional CINR based handover decision by the RSSI based one. In this case, the results of the RSSI based handover with hysteresis of 4 dB are the same as results of the proposed algorithm for $CINR_{T,out}$ = –5.7 dB.

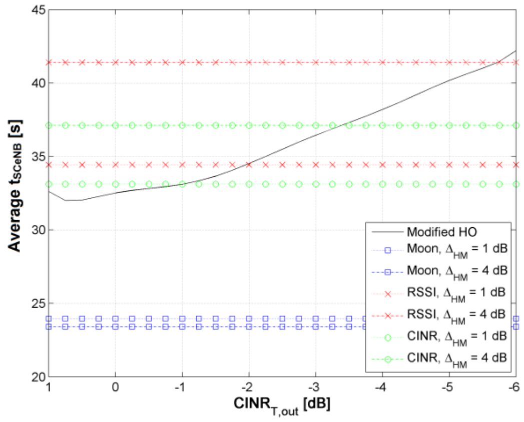


Figure 14: Average time spent by UEs in connected to the SCeNB

According to the results in Figure 14, it is profitable to either increase the hysteresis for the conventional algorithms or lower $CINR_{T,out}$ for the proposed scheme to increase t_{SCeNB}. However, higher hysteresis as well as lower threshold $CINR_{T,out}$ can negatively impact the handover outage probability.

The handover outage probability is the ratio of unsuccessful handovers to the overall number of the performed handovers during the simulations. As an unsuccessful handover is understood the handover during which the CINR level drops under the $CINR_{OL}$. According to Figure 15, the handover outage probability is constant up to $CINR_{T,out}$ = –2.3 dB for proposed algorithm. Then it rises rapidly and get steady at approximately 50 % of handover outage. This steep increase is caused by the fact that channel quality is not sufficient if the CINR level drops close to the $CINR_{OL}$.

The handover outage probability comparable with the proposed scheme can be obtained only by the conventional handover based on the CINR with very low hysteresis. Nevertheless, the proposal reaches nearly twice lower handover outage (8 % instead of 15 %). Simultaneously, t_{SCeNB} is prolonged by 9 % by the proposal as can be observed in Figure 14. If $CINR_{T,out}$ is above –2.5 dB, a half of handover fails by proposed procedure. The similar level of handover outage is reached either by the CINR based and the Moon's algorithm with hysteresis of 4 dB. However, in this case, the proposed procedure prolongs t_{SCeNB} by 14 % and 85 % comparing to the conventional CINR based and the Moon's algorithm, respectively, for $CINR_{T,out}$ = –6 dB (see Figure 14).

Although the RSSI based algorithm shows sufficient results in term of t_{SCeNB}, the outage is very high even for low hysteresis. It is due to not efficiently chosen times of the handover decision. It means the handover to the SCeNB and back to the MeNB is performed too late comparing to an optimum time instant.

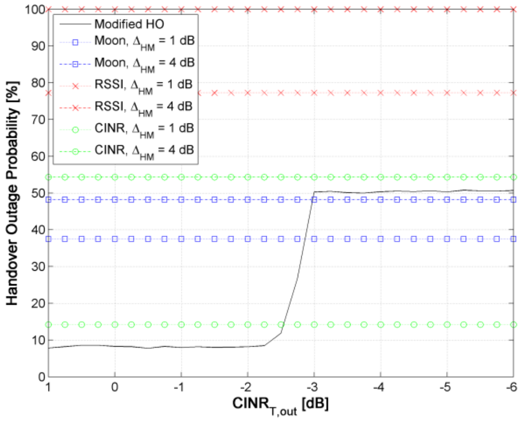


Figure 15: Handover Outage Probability over the threshold for handover to the MeNB

The results for t_{SCeNB} and handover outage probability can be summarized in two points. First, the proposal can significantly reduce the handover outage probability simultaneously with slight prolongation of t_{SCeNB}. This is the case when users do not accept high level of the handover outage (outage is reduced from 15 % to 8 % by proposed algorithm). Second, the modified handover algorithm significantly prolongs t_{SCeNB} and keeps roughly the same handover outage probability if users are willing to tolerate higher level (roughly 50 %) of the handover outage. Therefore, proposed algorithm is profitable for the user who prefers quality as well as for the user who aims low connection cost.

The number of handovers initiated by proposed algorithm is kept at nearly the same level as in case of the conventional handover. The simulation shows only 3 % and 5 % rise in the overall amount of initiated handovers comparing to the CINR and the RSSI based procedure, respectively. Comparing to the Moon's procedure, proposed algorithm reduces amount of handovers for approximately 4 %.

Figure 16 shows the percentage of overall simulation time spent by the UEs in a state of outage. The outage probability is the ratio of the time when the user's requirements are not fulfilled due to the CINR level under the $CINR_{OL}$ to the overall duration of the simulation.

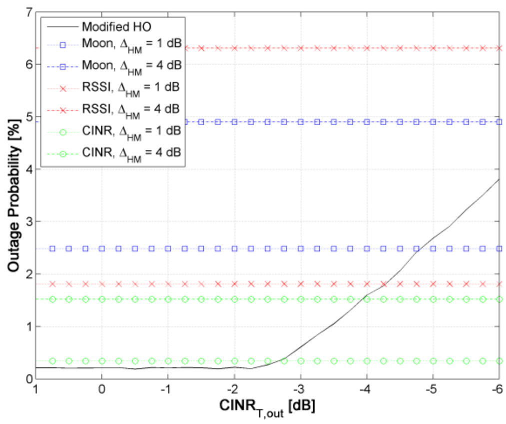


Figure 16: Outage Probability over the threshold for handover to the MeNB

The proposed scheme shows again a constant outage, of roughly 0.2 %, for $CINR_{T,out}$ up to –2.5 dB. This outage is the lowest of all evaluated algorithms. Then, the outage probability rises linearly with slope of 1 % per 1 dB for $CINR_{T,out}$ lower than –2.5 dB. The handover performed based on the comparison of the CINR reaches very low outage if the hysteresis is set to low value. Nevertheless, the outage is still nearly twice higher than the outage obtained by the proposed handover decision with $CINR_{T,out}$ up to –2.5 dB. All other algorithms are outperformed significantly by the proposed one.

Comparing to all three competitive algorithms, the proposed one provides highest extension of the t_{SCeNB} with lowest rise in the outage probability. In the proposed handover, the t_{SCeNB} can be adapted more significantly according to user's requirements on outage probability while the outage rises slowly comparing to other competitive techniques. Therefore, proposed modified handover algorithm is more suitable for consideration of the connection cost.

5.2.3 Optimum hand-out threshold level over connection cost ratio

As it is shown in the previous subsection, t_{SCeNB} rises with lowering $CINR_{T,out}$. It means, keeping users at the SCeNBs for a longer time introduces a benefit for the operator in the form of MeNBs offloading. However, the outage is also rising with decreasing $CINR_{T,out}$ and users suffer a loss in quality. Therefore, a sort of compromise between t_{SCeNB} and the outage probability must be found. The compensation this potential decrease in the quality to users by lower expenditures of users is proposed in this subsection. The lower connection cost provided via SCeNB, the higher hand-out hysteresis can be applied and vice versa. This enables to prolong the time spent by UEs in the SCeNB if the SCeNB provides connection for a lower cost than the MeNB. This way, an operator can give a benefit to the users that are willing to offload its network at the cost of higher outage.

For determining appropriate trade-off between the connection quality and cost, three illustrative types of users are defined. Each type represents an example of user's preferences on the outage probability over the connection cost. The first type, User *A*, is aimed primarily on the quality (i.e., low outage) regardless of the connection cost. An example of the User *A* is someone who requires high quality of voice calls. The second type, User *B*, is willing to compromise on the quality requirements for cheaper services. The third type of the user, User *C*, is focused on saving money and does not stress the quality of connection. This user can be seen as someone who uses mainly the services with low requirements on delay, such as e-mail, FTP, or HTTP.

An example of acceptable increase in outage probability over the connection cost ratio for all illustrative types of users is depicted in Figure 17. The "Cost Ratio" can be expressed as the ratio of the cost of the SCeNB's connection to the cost of the connection to the MeNB. For example, the ratio 1/1 means the same price of the connection via the SCeNB and the MeNB. In this case, the user has preferences for neither SCeNB nor MeNB in term of the cost. On the other hand, the ratio 0/1 corresponds to the situation when the connection via the SCeNB is for free.

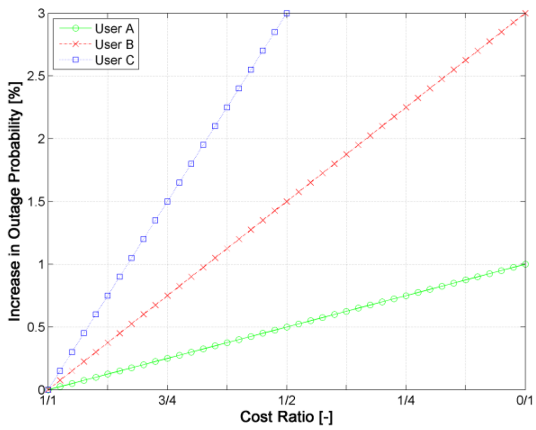


Figure 17: Acceptable increase in outage for different types of users over ratio of connection cost to SCeNB and MeNB

Based on the user's requirements and on the connection cost ratio (and depicted in Figure 17), optimum $CINR_{T,out}$ can be determined for each type of users. Figure 18 shows that the User *C* whose demands on the quality are the lowest can use lower level of $CINR_{T,out}$ (more negative numbers) than other users. The lower threshold results in higher probability of the outage as shown in Figure 16. However, the User *C* is willing to tolerate an increase in the outage as it prolongs t_{SCeNB} (see Figure 14) and thus it reduces the cost of connection.

In contrary, the User *A* prefers high quality regardless of higher connection cost. Therefore, higher threshold must be set to maintain an adequate quality of the connection.

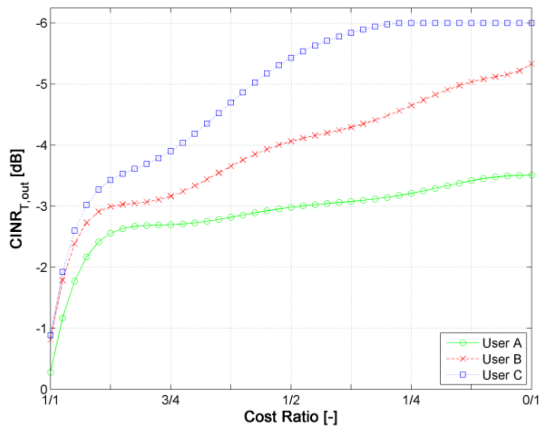


Figure 18: Threshold $CINR_{T,out}$ for handover to MeNB according user's requirements

In real networks, the threshold can be derived by an operator from Figure 18 as a fix value for all users, according to the quality the operator wants to provide. Another option is to let individual users choose their preferences on the quality and cost (as presented in Figure 17). Then the billing is performed according to the user's selection. It means the operator gives a benefit, e.g., in form of a lower price, to User *C* over User *A* since User *C* consumes fewer resources of MeNBs.

5.2.4 Discussion of results

In this Chapter, an enhancement of the conventional handover by a consideration of user's requirements on the quality of the connection with respect to the cost of the connection is proposed. This way, an operator can give a benefit to the users that are willing to offload its network at the cost of higher outage. The offloading is reached by prolongation of the time spent by the UEs connected to the SCeNBs instead of staying connected to the MeNB. To maximize the time spent by the UEs connected to the SCeNB, the conventional handover algorithm is modified.

At first, three different handover decision strategies are compared by modification of hand-out hysteresis to show their impact on the time in SCeNBs. As the results show, the most appropriate algorithm for the prolongation of time spent in SCeNB is the conventional handover decision based on CINR.

Later, the extension of the time in the SCeNBs is achieved by decreasing the hand-out CINR threshold $CINR_{T,out}$ for disconnection from a SCeNB. By this modification, the time spent in SCeNB can be prolonged significantly in comparison with hand-out hysteresis while the outage shows lower probability. Moreover this modification keeps the number of handovers at nearly the same level as in the case of conventional handovers.

Additionally, maximization of time spent in SCeNB by adjustment of the hand-out CINR threshold is proposed. It considers willingness of users to stay connected to the SCeNB for a longer time if the cost of connection provided via SCeNBs is lower than via the MeNB. The longer time spent in SCeNB is associated with the shorter time in MeNB and thus with offloading of the MeNBs. As results show, for users who want to save for connection or who don't care about short term quality of their connection, the lower level of $CINR_{T,out}$ is suitable. On the other hand, users who prefer high quality of connection select higher level of $CINR_{T,out}$ for ensuring of sufficient QoS.

6. Neighbor Cell List management and scanning in networks with SCeNBs

The problem of NCL generation arises especially when the SCeNB or MeNB is newly connected to the cellular network and if SCeNBs are in neighborhood of the new cell. The new cell does not know its neighborhood and neighbor cells do not know about the new cell.

Although the problem of creation and maintenance of the NCL can be solved manually as in case of network equipped only with the MeNBs, a huge number of the SCeNBs prevents the manual configuration of the NCL of each SCeNB or overlapping MeNB. Moreover, in case of HeNB, the manual creation and maintenance of NCL is not possible since the owner of the HeNB can turn it on/off or move it anytime. The conventional algorithms developed for network only with the MeNBs cannot be efficiently used since specifics of network with the SCeNBs are not taken into account. In case of the UEs connected to the recently deployed SCeNB, the main problem is identification of all possible neighbor cells. On the other hand, in case of newly installed MeNB, the main issue is efficient reduction of a huge number of potential neighboring cells. These two main problems are solved by proposed algorithms introduced in following sections.

6.1 Self-configuration of NCL of new connected SCeNBs

In this section, a simple approach for creation of the NCL of new installed SCeNBs is proposed. In the first subsection, the proposed approach is described. The second subsection presents evaluation of the proposed algorithm. Note that the proposed approach focuses especially on simplicity and fast convergence of the new NCL with reduction of missing neighboring cells suitable for scanning.

6.1.1 Algorithm for self-configuration of NCL of new installed SCeNBs

The problem of SCeNB's NCL generation arises when the SCeNB is newly connected to the network. The new installed SCeNB ($SCeNB_n$) have no information about its neighborhood and also neighbor cells do not know about the new $SCeNB_n$. Therefore, no information can be provided to UEs connected to neighboring cells and handover to $SCeNB_n$ is not possible. It leads to underutilization of $SCeNB_n$. $SCeNB_n$ can be found only by scanning of the whole bandwidth by using ANR [63] or DSR [64]. In case of connection to $SCeNB_n$, UEs do not have any information about potential handover candidates. To avoid of drop of connection, UEs connected to $SCeNB_n$

have to again perform scanning of the whole spectrum. This leads to additional delay and potentially to handover failure. Moreover, scanning of whole spectrum is more energy-consuming.

This simple approach proposes the algorithm of creation of NCL of new installed SCeNBs. Proposed algorithm reduces delay of searching the neighborhood of $SCeNB_n$ by introduction of so-called Temporary NCL (TNCL). Proposed algorithm of creation of NCL of new connected SCeNB is composed of two parts: i) identification of potential neighboring cells and creation of TNCL and ii) minimization of size of TNCL to NCL containing real available neighboring cells only.

In the first part, proposed approach assumes that each SCeNB is able to receive signal from at least one MeNB. Based on the received signal from MeNB, a coarse position of $SCeNB_n$ can be determined. The approximate position of the $SCeNB_n$ is sent to the temporary location database of SCeNBs over backhaul. All potential neighbors of $SCeNB_n$ are identified based on the coarse position of the $SCeNB_n$. The number of possible neighbors is related to the accuracy of estimation of the position of $SCeNB_n$ as well as the position of all SCeNBs in its neighborhood. The list of all potential neighbors, denoted as TNCL, is sent to the $SCeNB_n$. Subsequently, information on the new SCeNB is sent to all SCeNBs in its potential neighborhood. Thereafter, all UEs connected to $SCeNB_n$ are used TNCL for scanning of neighborhood and looking for the appropriate handover candidate.

By dense deployment of SCeNBs and/or by raising the inaccuracy of position determination, the size of the TNCL can significantly rise, although the SCeNBs are not the real neighbors. It leads to additional delay and rising of consuming of energy caused by scanning. Thus the TNCL, created after the connection of the $SCeNB_n$ into the network, have to be reduced to NCL only. Therefore, after creation of TNCL, the process of minimization is follows. The process of minimization is based on handover history algorithm [72]. For given number of handovers, the TNCL is distributed and all connected UEs are scanning all potential neighboring cells contain in TNCL. If a UE performs handover from/to $SCeNB_n$, the neighboring cell of $SCeNB_n$ is added to its regular NCL. After performing sufficient number of handover to/from $SCeNB_n$, all SCeNBs to/from which UEs perform at least one handover remains in the regular NCL while all other SCeNBs, to/from which no UE perform handover during this period, will be removed together with TNCL. In other words, the TNCL is replaced by NCL containing only real neighbors identified by observing the handovers when the real NCL is completely set up. The scheme of creation of NCL in new installed SCeNB is depicted in Figure 19.

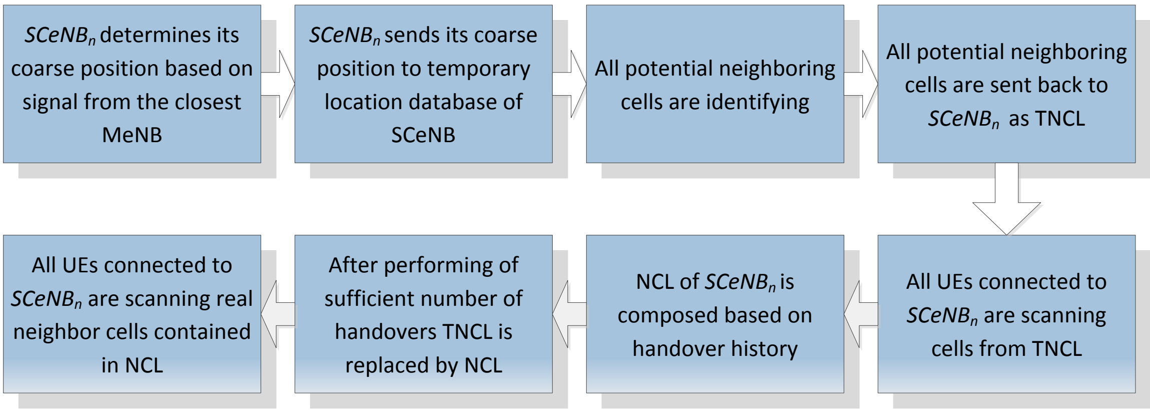


Figure 19: Proposed approach for creation of NCL of new connected SCeNB

6.1.2 Efficiency evaluation of self-configured NCL of SCeNB

The efficiency of proposed algorithm is observed in three following simple evaluations: i) new records added in all NCLs; ii) ratio of discovered neighboring cells and iii) delay caused by scanning. As simulation environment, model and parameters described in subsection 4.2.1 is used.

Figure 20 shows the ratio of number of new record in all NCLs of all SCeNBs related to the total number of records in the whole scenario over the amount of users passing the street. The maximal number of records in the scenario is 42. When handover is performed between two SCeNBs, who know not each other yet, two records (to each NCL one) are performed.

The highest amount of new records written to NCLs is performed during the first passing user. The ratio of new record to total number of record in the first users passing the street is 22 %. Then, the number of new records decreases with increasing number of amount of users passing the street. Only negligible amount of new records is created after 10 users passing the street.

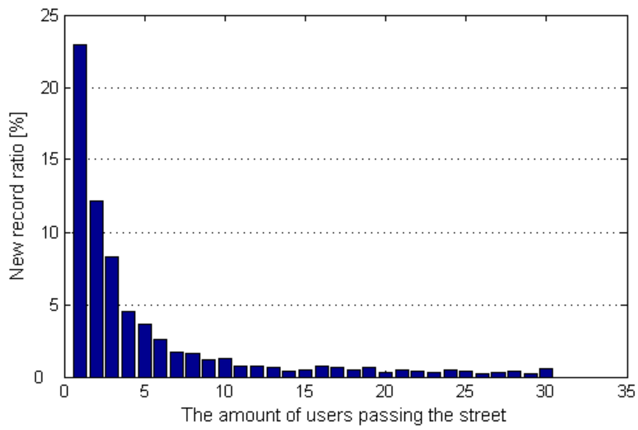


Figure 20: Trend of amount of new records added in all NCLs over the amount of users passing the street

Figure 21 shows the ratio of the number of discovered neighborhood cells to the total number of available cells for particular SCeNB in the whole scenario over the amount of users passing the street. The results are observed at the SCeNB in the middle of length of the street (the red one in Figure 7). The SCeNBs has 5 neighboring SCeNBs and one neighboring MeNB

(MeNB is not considered in NCL, because the handover cannot be executed due to the signal levels experienced in the street).

Two records are added to the NCL while the UE visits the SCeNB for the first time (one record for the cell which is entered by UE and one for the cell of which the UE went out). The ratio of discovered neighbors increases with the number of visited serving SCeNBs. Three records are in NCL approximately after fifth visit. Further increase of the number of new neighbors is not significant.

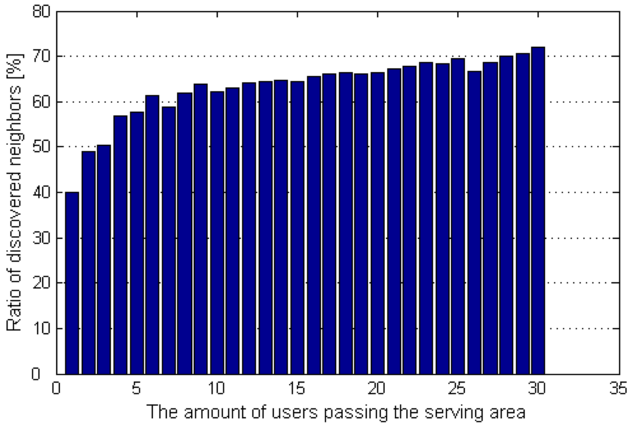


Figure 21: Ration of the number of total record in NCL to total number neighbor cell for particular SCeNB

Since before the NCL is exploited the TNCL is used, the analysis of a period required for adding of sufficient number of neighboring cells to NCL is also investigated.

Figure 22 shows the average delay after the certain number of completed passing the street by users. The curves “Empty NCL” assume no SCeNB in NCL at the beginning of NCL’s management. The curves “Temporary NCL” represent the average delay caused by searching the TNCL. The amount of SCeNBs for scanning in case of TNCL corresponds to the number of identified neighbors based on the coarse determination of SCeNBs position. The different amounts of SCeNBs (i.e. 6, 12, and 18) express the amount of SCeNBs that are determined as potential neighbors according to the signal received from MeNB. In the investigated scenario, each SCeNB (excluding SCeNBs at the edge of the street) has five real neighboring SCeNBs.

Figure 22 shows that the highest delay occurs in the first passing while using empty NCL. Then, the average delay drops rapidly. In case of TNCL, the delay is invariable disregarding the amount of passing users. In this proposal, the TNCL is used until a number of users’ passes through is reached. If exact number of passes is performed, the TNCL is replaced by NCL containing only cells involved in at least certain number of handover. In this paper, the TNCL is replaced by the NCL containing only stations to which/from which was performed at least one handover. The figure shows that the number of required passes (executed handover) is different for different numbers of surrounding cells.

Note, that no advantage of introduction of TNCL is achieved for 18 or more surrounding cells as the average delay due to TNCL is always higher than in case of empty NCL. It means in case of deploying of $SCeNB_n$ into environment with more than 18 surrounding cells, the autonomous scanning algorithm such as ANR [63] or DSR [64] is suitable to use.

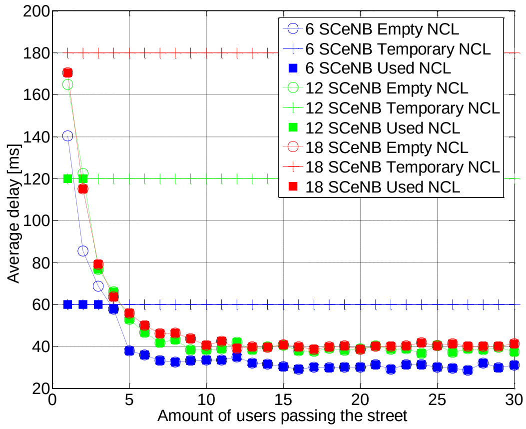


Figure 22: Average delay caused by scanning

6.2 Self-configuration of NCL of MeNBs

In this section, the proposed algorithm for the self-configured NCL of MeNBs in the network with SCeNBs is defined. The algorithm targets especially on the NCL management for the UEs connected to the MeNBs (denoted as MUEs). The proposal can be also used for management of the NCL of UEs served by the SCeNBs (denoted as SCUEs). However, as it is explained later in this section, benefits for the SCeNBs are limited due to the fact that case when a SCeNB covers several underlying SCeNBs is not expected to be often in real networks. Therefore this section focuses only on the NCL of MUEs.

The proposed approach is based on handover history. Using the conventional handover history [72] for the NCL of MeNBs could lead to an addition of a large number of neighboring cells especially in the network with the dense deployment of the SCeNBs. All of these cells are neighboring cells of the MeNB since it is possible to perform handover to all of these cells. However, by considering SCeNBs in the network, given neighboring cell is not always directly accessible from the current location of a UE. In other words, in the network with SCeNBs, it is not always possible to go from one cell to other cell just through the MeNB without passing through another cell. This principle of obstructed paths on the way from one cell to another is a main idea of proposed algorithm.

This main idea of proposed algorithm is shown in Figure 23. In this example, four SCeNBs are placed along the street under coverage of one MeNB. The handover from the MeNB to each SCeNB is possible. Thus, based on the conventional handover history algorithm [72], the MeNB contains all SCeNBs in its NCL. However, as it is illustrated in Figure 23, after performing handover from the $SCeNB_3$ to the MeNB it is impossible to perform handover directly to the $SCeNB_1$. The path to the $SCeNB_1$ is obstructed by the $SCeNB_2$ and cannot be bypassed on the way to the $SCeNB_1$. It means beside the principle of obstructed paths, also the knowledge of previous visited cell is the base of proposed algorithm. The description of proposed algorithm exploits obstructed paths and knowledge of previous visited cell is provided in the following subsection.

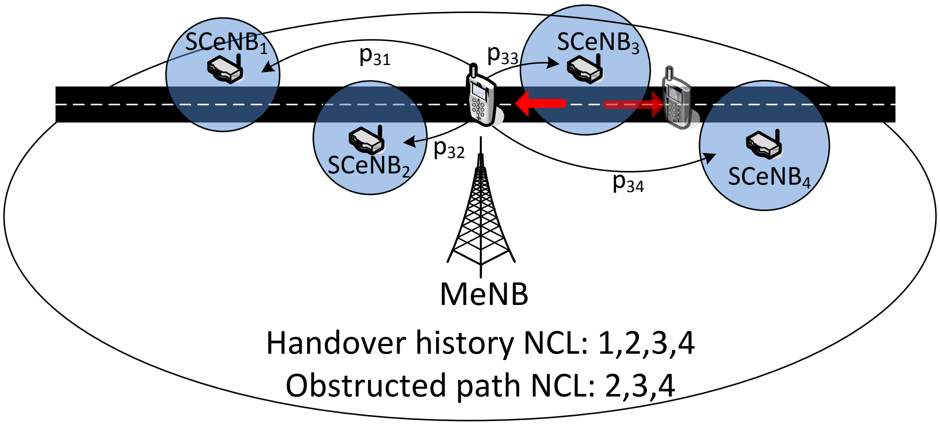


Figure 23: Principle of obstructed paths

6.2.1 Obstructed paths and knowledge of previous visited cell

To easily follow and understand the proposal, notations used in the proposal description are summarized in Table 8.

Notation	Description
$cell_\alpha$ / $cell_\beta$	originating cell from which a MUE can perform handover to $MeNB_M$ / destination cell to which a MUE can perform handover from $MeNB_M$
B_M / A_M	set of all cells to/from which the handover from/to $MeNB_M$ is possible
$p_{M\beta}$ / $p_{\alpha M}$	probability of handover from $MeNB_M$ to $cell_\beta$ / from $cell_\alpha$ to $MeNB_M$
$p_{\alpha M\beta}$	probability of handover from $MeNB_M$ to $cell_\beta$ after handover from $cell_\alpha$ to $MeNB_M$
B_{M_α}	set of distant neighbors of $cell_\alpha$ that can be reached through $MeNB_M$
$cell_x$ / $cell_y$	any cell within the $MeNB_M$ coverage ($cell_x$ / $cell_y \in (A_M \cup B_M)$)
v_{avg}	average speed of MUE computed after passing through the $MeNB_M$
$t_{\alpha M\beta}$	time between handover from $cell_\alpha$ to $MeNB_M$ and handover from $MeNB_M$ to $cell_\beta$
D_M / $d_{\alpha\beta}$	distance matrix of $MeNB_M$ containing the minimum distances between cells under coverage of the $MeNB_M$ / D_M contains elements $d_{\alpha\beta}$ expressing distance from $cell_\alpha$ to $cell_\beta$
$d_{\alpha\beta\_UE}$	distance from $cell_\alpha$ to $cell_\beta$ calculated by particular MUE
D_{M_α}	set of minimal distances between $cell_\alpha$ and distant neighbors of $cell_\alpha$ reachable through the $MeNB_M$
v_{est} / v_{real}	estimated speed of UE / real speed of UE
T_{M_α} / $t_{\alpha\beta}$	set of minimum time distances between $cell_\alpha$ and distant neighbors of $cell_\alpha$ reachable through the $MeNB_M$ / T_{M_α} contains elements $t_{\alpha\beta}$ expressing minimum time distance between $cell_\alpha$ and $cell_\beta$ reachable through the $MeNB_M$ calculated from estimated speed

$T_{M\_\alpha\_GI}$ / $t_{\alpha\beta\_GI}$	set of minimal distances expressed by means of time between $cell_\alpha$ and distant neighbors of $cell_\alpha$ reachable through the $MeNB_M$ considering the guard interval GI / element of set $T_{M\_\alpha\_GI}$
v'_{meas} / v'_{pre}	error in measurement of speed / error in speed estimation
v_{inac}	inaccuracy of speed determination ($= v'_{meas} + v'_{pre}$)
S_{MUE}	set of scanned cells defined for each MUE moving through the $MeNB_M$

Table 8: Notation used for proposed scanning algorithm

Let's assume N_{net} is the set of all cells (MeNBs as well as SCeNBs) in the network. The handover is performed at the edge of cells. In order to perform the handover from MeNB correctly, the NCL of MUEs should include all cells, to which the probability of handover from the serving $MeNB_M$ is higher than threshold p_{thr}. The set B_M comprising all neighboring cells of the $MeNB_M$ is defined as follows:

$$B_M = \{cell_\beta \in N_{net} \mid p_{M\beta} > p_{thr}\} \tag{13}$$

where $p_{M\beta}$ is the probability of handover from $MeNB_M$ to the neighboring cell $cell_\beta$. In real networks, the probability of handover $p_{M\beta}$ is observed by statistical evaluation of all previously performed handovers from the $MeNB_M$. The threshold p_{thr} must be adjusted for optimization of the performance [82]. With a higher value of the threshold, less neighboring cells are scanned and therefore, more potential handover candidates can be missed. Since proposed algorithm aims on maximization of SCeNBs' utilization, the threshold is set to $p_{thr} = 0$.

Since the B_M contains all possible handover candidates of the $MeNB_M$, this set corresponds to the Neighbor Relation Table (NRT) in 3GPP [39]. However, using all possible handover candidates for scanning is ineffective. Therefore, the NCL for each MUE using knowledge of the previous visited cell and available paths between cells is derived. The number of scanned cells (included in B_M) when the UE is moving through the $MeNB_M$ can be reduced by using principle of obstructed paths and knowledge of the cell visited before the $MeNB_M$ (denoted as previous visited cell).

Obstruction of the path between cells is phenomenon occurring if the cell with small coverage radius (e.g., SCeNB) is deployed within the radius of a large cell (e.g., MeNB). Without deployed SCeNBs, each user can pass from one side of MeNB to another without handover. However, if SCeNBs are deployed, the MeNB's cell overlaps with SCeNBs. When a SCeNB spans over the entire width of the street, the path is obstructed by this SCeNB. Thus, if the user is moving along this street, handover to the SCeNB is performed since the path is obstructed by this SCeNB. With increasing density of SCeNBs, more paths become obstructed from the MeNB point of view.

The principle of obstructed paths complemented with knowledge of the previous visited cell, labeled as $cell_\alpha$, enables to determine limited set of really accessible cells. At first, set of all potential previous visited cells has to be defined. This set, denoted as A_M, contains all cells from which the handover to the $MeNB_M$ is possible (note that this set do not need to be the same as set of B_M due to hysteresis for handover):

$$A_M = \{cell_\alpha \in N_{net} \mid p_{\alpha M} > p_{thr}\} \quad (14)$$

where $p_{\alpha M}$ represents the probability of handover from the $cell_\alpha$ to the $MeNB_M$.

By exploiting the knowledge of the previous visited $cell_\alpha$ and a principle of obstructed paths, particular $cell_\alpha$ is known after handover to $MeNB_M$ is performed and the set B_M can be narrowed down to the set B_{M_α} defined by the subsequent formula:

$$B_{M\_\alpha} = \{cell_\beta \in B_M \mid (p_{\alpha M\beta} > p_{thr}) \wedge (cell_\alpha \in A_M)\} \quad (15)$$

where $p_{\alpha M\beta}$ represents the probability of handover from the $MeNB_M$ to the $cell_\beta$ if the user comes to the $MeNB_M$ from the particular $cell_\alpha$. In other words, the set B_{M_α} contains all cells, which can be reached from the $MeNB_M$ if the MUE's last visited cell was $cell_\alpha$. This set of cells is denoted as Distant Neighbor Cells (DNCs) of the $cell_\alpha$. The NCL of MUE can be reduced to only the cells included in the set B_{M_α} after the handover from the $cell_\alpha$ to the $MeNB_M$ is performed. Note that the set B_{M_α} includes also $cell_\alpha$, since the MUE can turn and go back to the $cell_\alpha$ any time. Also note that not only SCeNBs but also MeNBs can be included in both A_M and B_M. As can be seen from (15), the B_{M_α} is always subset of the B_M, i.e., $B_{M\_\alpha} \subseteq B_M$.

Benefits of the principle of obstructed paths and of the knowledge of previous visited cell can be demonstrated by example shown in Figure 24. In a conventional way, the MUE has to scan 10 neighboring cells (9 SCeNBs + 1 MeNB) belonging to B_2 during the movement of the MUE within the area of $MeNB_2$. Contrary, if the proposed approach is considered, the MUE scans only 4 neighboring cells (i.e. $SCeNB_{13}$, $SCeNB_{10}$, $SCeNB_{15}$, and $SCeNB_{14}$) belonging to B_{2_14} after the MUE leaves $SCeNB_{14}$ and attaches to the $MeNB_2$.

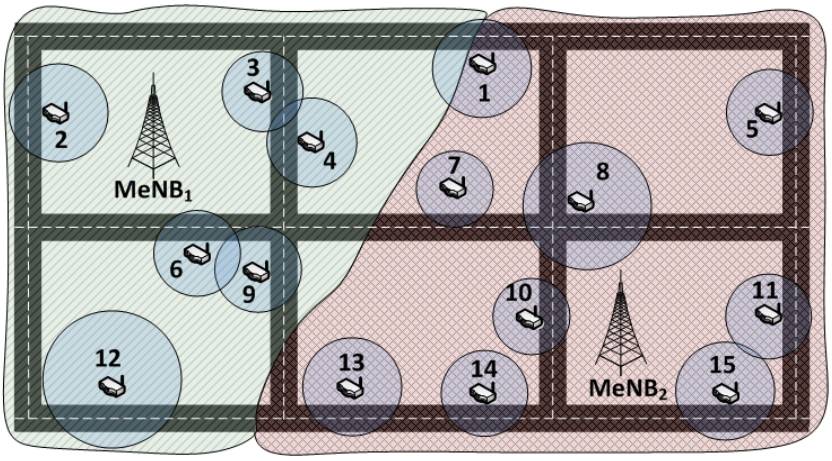


Figure 24: Example of network deployment

For the expression of DNC relations among all cells within the $MeNB_M$ coverage, the graph theory is adopted. For each $MeNB_M$ in the network, the graph G_M (V_M, E_M) is defined. The set of vertices (V_M) of the graph G_M represents all cells from which the handover to the $MeNB_M$ is possible or to which the handover from the $MeNB_M$ is possible (i.e., $A_M \cup B_M$). The set of edges (E_M) of the graph shows the links between DNCs. The degree of any vertex x denoted as $d(v_x)$ implies the number of DNCs and therefore the number of cells that need to be scanned by the MUE after performing handover from a general $cell_x$ to the $MeNB_M$ (i.e., in case that $cell_x$ becomes previous visited cell $cell_\alpha$).

The example in Figure 24 can be interpreted by two graphs as shown in Figure 25. For the clarity of graph expression, the edges from any vertex x to the same vertex (i.e., v_x, v_x) corresponding to cases $cell_\beta = cell_\alpha$ are not depicted in Figure 25 as this path is applicable for all cells (as explained above). Handover at the edge of cells is assumed in this example. Thus, if handover from any $cell_x$ to the $MeNB_M$ and then to any $cell_y$ is possible (i.e., $cell_y$ is DNC of $cell_x$), the handover from $cell_y$ to the $MeNB_M$ and then to the $cell_x$ is also possible. However in real network (and as well in following simulation), hysteresis is exploited to avoid redundant handovers. Consequently DNC relations may not be reciprocal.

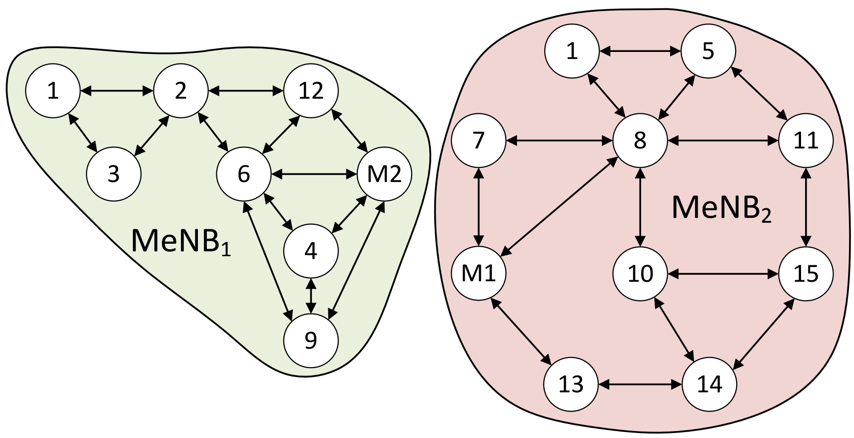


Figure 25: Expression of distant neighbor cell relations by graph theory

The examples in Figure 24 and Figure 25 show few typical cases, which can occur in the network. The first case is the direct neighborhood of two cells, e.g., $SCeNB_3$ and $SCeNB_4$ in Figure 24. Users passing from the $SCeNB_3$ to the $SCeNB_4$ do not pass through $MeNB_1$. Therefore, these two cells are not DNCs and consequently, the cells are not interconnected by edge in Figure 25. Of course, both SCeNBs must be included in their own NRT so they are aware of each other.

Another situation appears when two cells are direct neighbors as well as DNCs. It means handover directly between two cells as well as the handover through the MeNB are possible. In Figure 24, this case is represented, e.g., by $SCeNB_6$ and $SCeNB_9$. From the $MeNB_1$ point of view, these two cells are regular DNCs. Thus this relation is represented by edge in Figure 25.

Analogical case is that the SCeNB obstructs only a part of the road as, e.g., $SCeNB_7$. When the UE leaves, for example, $SCeNB_8$, it is possible to bypass $SCeNB_7$ and enter directly the

$MeNB_1$. In this case, all DNCs of $SCeNB_7$ are also DNCs of each other among themselves. This is again reflected by edges between $MeNB_1$ and $SCeNB_8$ in Figure 25. Note that if a SCeNB spans over more MeNBs (such as $SCeNB_1$ in example), then it is included in all G_M belonging to all MeNBs which overlap with the SCeNB.

As mentioned before, the described principle for definition of the NCL of MeNB can be used also for SCeNBs. However, the problem of large NCL is related primarily to the MeNBs covering large number of SCeNBs. With the decreasing radius of cell, the number of cells under the coverage of the cell from upper tier is decreasing. It means that all underlying neighbors are available from almost all places in the SCeNB coverage. Consequently, the NCL of SCUE composed according to proposed algorithm (set B_{M_α}) is usually identical with the set B_M (NRT of SCeNB).

6.2.2 Transition probability

The probability of transition among cells for $MeNB_M$ in the network can be expressed by transition matrix, P_M, derived from the amount of handover performed in the past. Generally, each element of the transition matrix, $p_{\alpha M\beta}$, represents the probability of transition from the $cell_\alpha$ to the $cell_\beta$ through the MeNB. A general transition matrix is defined as:

$$P_M = \begin{pmatrix} p_{1M1} & \cdots & p_{1M\beta} & \cdots & p_{1Mm} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ p_{\alpha M1} & \cdots & p_{\alpha M\beta} & \cdots & p_{\alpha Mm} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ p_{nM1} & \cdots & p_{nM\beta} & \cdots & p_{nMm} \end{pmatrix} \tag{16}$$

where $\alpha = \{1, 2\ldots, n\}$ and $n = |A_M|$ is the total number of cells from which handover to the $MeNB_M$ can be performed; similarly $\beta = \{1, 2\ldots, m\}$ where $m = |B_M|$ is the total number of cells to which the handover from the $MeNB_M$ can be performed. The neighboring cells including both underlying SCeNBs as well as neighboring MeNBs. The simple example of transition matrix obtained for the $MeNB_M$ in Figure 23 can be expressed as follows:

$$P_M = \begin{pmatrix} p_{11} & p_{12} & 0 & 0 \\ p_{21} & p_{22} & p_{23} & 0 \\ 0 & p_{32} & p_{33} & p_{34} \\ 0 & 0 & p_{43} & p_{44} \end{pmatrix} \tag{17}$$

where $p_{\alpha M\beta}$ and 0 implies nonzero and zero probability of the handover to the $cell_\beta$ after the handover from $cell_\alpha$ to the $MeNB_M$ was performed, respectively.

Each row of the transition matrix is associated with cell, from which the handover to the MeNB is performed. Thus:

$$\sum_{\beta=1}^{d} p_{\alpha M\beta} = 1 \qquad (18)$$

For example shown in Figure 23, the probability of handover from the $SCeNB_3$ (row 3 in (17)) to the $SCeNB_1$ is $p_{31} = 0$. Therefore, this cell is not considered for scanning by the UE leaving the $SCeNB_3$. All other cells are considered for scanning as the probability of handover to these cells is nonzero. These cells, i.e., $SCeNB_2$ and $SCeNB_4$, are denoted as distant neighbors of the $SCeNB_3$. Note that the UE must scan also the $SCeNB_3$, since the UE can turn and go back. Thus, the NCL delivered to a UE, which performs handover from the $SCeNB_3$ to the MeNB contains cells $SCeNB_2$, $SCeNB_3$, and $SCeNB_4$.

The process of discovery of distant neighbors is shown in Figure 26. The algorithm is based on the handover history extended by the knowledge of previously visited cell. Note that proposed algorithm is intended for the MeNBs and optimization of the NCL of the SCeNBs is out of scope of this section. Therefore, for the simulations, it can be assumed that the NCL of SCeNBs always contains all potential neighbors. It means, the NCL of SCeNBs is complete and all handovers performed from the SCeNBs during the simulation are faultless. This assumption does not affect simulation results.

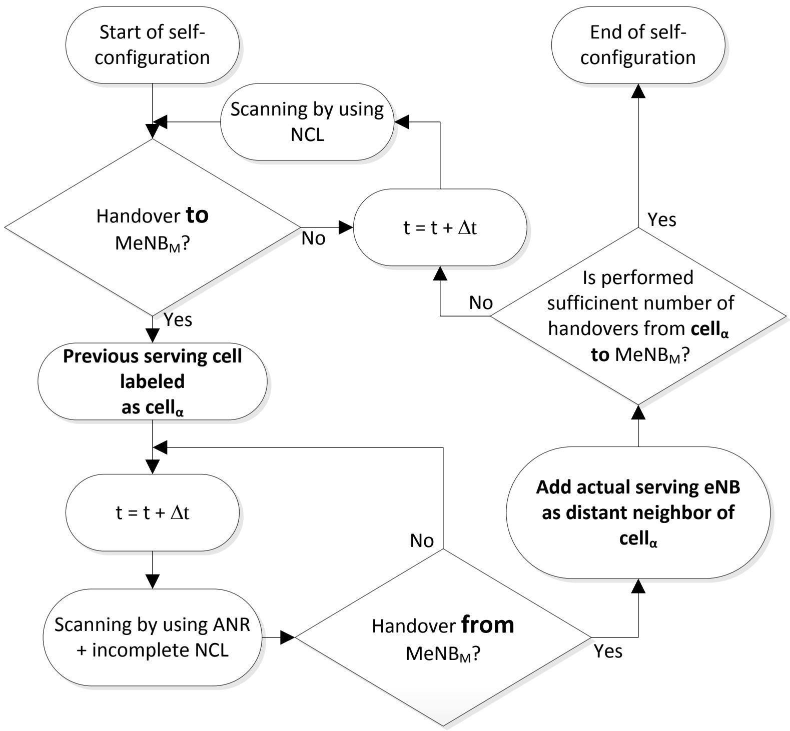


Figure 26: Process of learning of distant neighboring cells (main steps are highlighted)

During the first few handovers after installation of a new $MeNB_M$ the NCL of the $MeNB_M$ is not available or it is incomplete. Therefore, when the UE is served by the $MeNB_M$, the ANR [63] in combination with the incomplete NCL is used by the UE for distant neighbor cells discovery.

The discovery of distant neighbors is proposed to be as follows. When a UE performs handover to the $MeNB_M$, the previous serving cell (any cell, from which the handover to the $MeNB_M$ is performed) is labeled as $cell_\alpha$. Thereafter, when the handover from the $MeNB_M$ is performed, a new serving cell (any cell, to which the handover from the $MeNB_M$ is performed) is assigned as a distant neighbor of the $cell_\alpha$. It means, the probability of transition from the $cell_\alpha$ (row α) to the new serving cell (column β) is increased (and it becomes nonzero) in the transition matrix of the $MeNB_M$.

The designation of particular cell as the $cell_\alpha$ lasts until a handover from the $MeNB_M$ to a neighboring cell is performed. After another handover to the $MeNB_M$, the cell from which the handover is performed is again labeled as the $cell_\alpha$. This algorithm is repeated for all neighboring cells of the $MeNB_M$, from which the handover to the $MeNB_M$ can be initiated until a sufficient number of the handovers is performed. It means the duration of self-configuration phase of the NCL can be different for individual neighboring cells. Thereafter, only cells with $p_{\alpha M\beta} > 0$ in row α of transition matrix P_M are scanned by the UE that performed handover from the $cell_\alpha$ to the $MeNB_M$. This way, the self-configured NCL is established.

6.2.3 Efficiency evaluation of self-configured NCL of MeNB

In this subsection, the average number of cells in the NCL is evaluated. Further the ratio of the number of handovers to the cells not presented in the NCL to the total number of handovers is shown. Proposed approach is compared with sensing (RSSI threshold of –110 dBm) and handover history algorithms based on the [37] and [72], respectively. For purposes of deeper comparison of presented proposal with the handover history algorithm, the self-optimization algorithm according to [82] is considered to take place after self-configuration phase for specific evaluations.

Figure 27 shows the average number of neighboring cells in the NCL in dependence on the number of deployed SCeNBs after the self-configuration phase is completed. As can be seen, proposed approach denoted as obstructed path shows the lowest number of neighboring cells over all densities of the SCeNBs. The amount of neighboring cells is nearly the same as in the case of the handover history for low number of SCeNBs. However, with an increase in the density of SCeNBs, the ways become more and more obstructed. Thus, the number of neighboring cells for proposed approach decreases and gain with respect to both competitive algorithms becomes more significant.

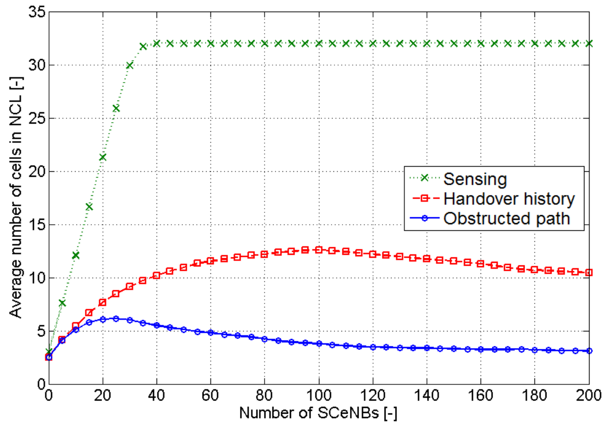


Figure 27: The average number of neighboring cells after self-configuration

The number of neighboring cells obtained by the handover history rises with the density of SCeNBs up to 100 SCeNBs. Thereafter, the streets are heavily covered by SCeNBs and, therefore, the handover to the MeNBs is less likely. Thus, the amount of neighboring cells decreases. For the sensing approach, the average number of cells in the NCL is the highest out of all algorithms. When the amount of the SCeNBs in the simulation exceeds the number of 40, the number of neighboring cells reaches the maximum size of NCL supported by LTE-A (32 cells). The average number of cells in the NCL is reduced by proposed algorithm by up to 70 % and 90 % comparing to the handover history and sensing algorithms, respectively.

Based on the handover statistics collected during the self-configuration for the handover history and the proposed algorithm, the number of cells in the NCL can be further reduced in self-optimization phase. The sensing exceeds the size of NCL even for relatively sparse density of SCeNBs deployment and therefore it is not taken into account in further evaluation of an impact of the self-optimization phase.

In Figure 28, the average number of neighboring cells in the NCL after self-optimization in dependence on the number of deployed SCeNBs is depicted. The self-optimization is performed by pruning of cells in the NCL with the probability of handover under a threshold as described in [82]. The threshold for pruning (T_p) is set to 1 % ([82]) and 5 %. In other words, only cells from row α of P_M with $p_{\alpha M\beta} > 1$ % and $p_{\alpha M\beta} > 5$ % are scanned, respectively.

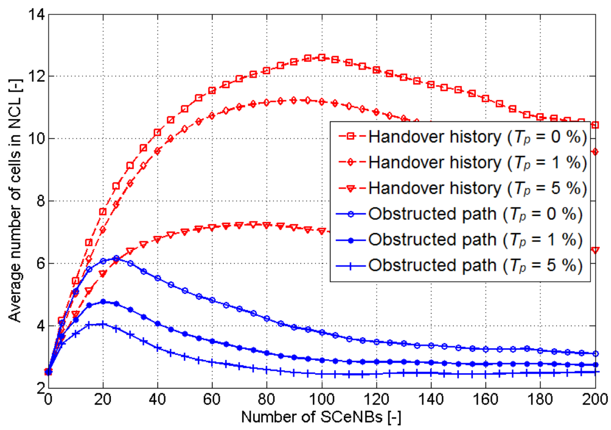


Figure 28: The average number of neighboring cells after self-optimization

For the T_p = 1 %, the number of cells in the NCL is reduced approximately by two and one cells in case of the handover history and the proposed algorithm, respectively. Using T_p = 5 % for pruning, the number of cells in the NCL is reduced by up to 6 cells (reached for 100 SCeNBs) by the handover history. The reduction for the proposed algorithm is up to two cells. Although the reduction of the number of neighboring cells is significant, the number of cells in the NCL for the handover history is still higher than for the proposed algorithm.

Although it is possible to decrease the number of neighboring cells for the handover history by high T_p significantly, it can emphasize the problem of missing handover target cell in the NCL.

Figure 29 shows the ratio of the number of handovers to the cells, which are missing in the NCL due to the self-optimizing phase to the total number of handovers. After self-configuration (before pruning), the ratio is equal to zero for both the handover history and for the proposed algorithm. After the pruning, the number of handovers to the cells which are not presented in NCL rises.

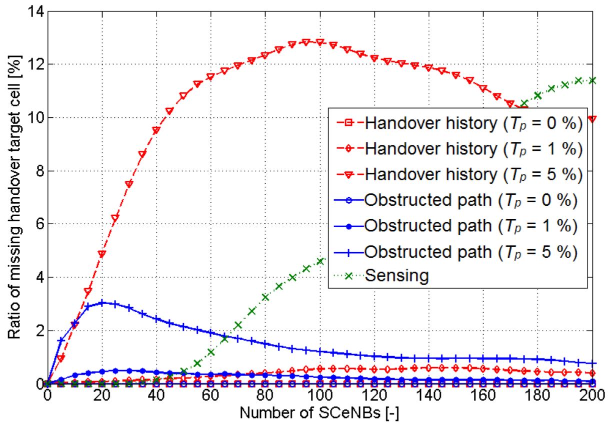


Figure 29: Ratio of the number of handovers performed to the missing cells to the total number of handovers

By using T_p = 1 %, the ratio of the number of handovers to the missing cell varies around 0.5 % for both the handover history and the proposed algorithm. For T_p = 5 %, the ratio for the handover history increases very fast with the density of deployment of SCeNBs up to 100 SCeNBs when it reaches 13 %. The maximum ratio for the proposed algorithm is 3 % (reached for 20 SCeNBs). With the rising density of deployment, the number of handovers to the missing cells decreases due to high coverage of the area by SCeNBs as explained in Figure 27.

The difference in the ratio of the number of handovers to the missing cells between the handover history and the proposed algorithm is due to the more uniform distribution of probability of handover to the individual neighboring cell for the handover history. It means there are a large number of cells with the similarly low probability in the NCL of MeNB in network with the dense deployment of SCeNBs. Based on T_p = 5 %, these cells are pruned (Figure 28) and it leads to the significant rise in the number of missing cells in Figure 29. On the contrary, the network with dense deployment of the SCeNBs is divided into the smaller parts with the more dispersal probability of handover to the individual neighboring cell by the proposed principle of obstructed paths.

The ratio of number of handovers to the missing cell in case of the NCL created by the sensing is zero only up to 40 SCeNBs. With the further rise in density of the SCeNBs, the number of handovers to the cells, which are missing in the NCL, is rises with linear tendency.

The advantage of sensing is that the self-configuration be performed before a new MeNB starts to serve users. As can be seen in Figure 30, both the handover history and the proposed algorithm require sufficient number of handovers to finish self-configuration phase and to obtain usable NCL. Figure 30 shows the average number of the missing cells in NCL during the self-configuration stage for 100 SCeNBs in scenario in dependence on number of handover performed to the MeNB.

Proposed algorithm needs approximately twice as much handovers to complete the list of cells in the NCL than the handover history (i.e., before the number of missing cells is zero). However, we have to keep in mind that the learning process in the self-configuration phase has to be performed only once for the new MeNB. If the new cell is added or removed from area of the MeNBs coverage, the NCL can be modified in self-optimization phase.

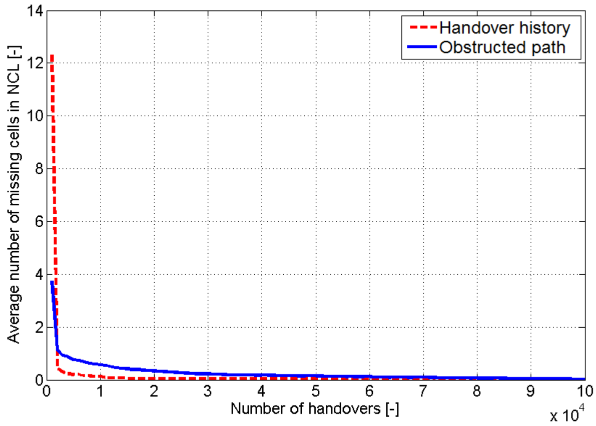


Figure 30: Average number of missing cells in NCL over number of performed handovers to the MeNB

6.3 Distance-based scanning algorithm

The drawback of previous described principle obstructed path is that during the whole movement of MUEs through the MeNB, the MUE have to scan all cells included in the B_{M_α} no matter what is the distance between the MUE and the DNC. Therefore, an estimation of the distances between the $cell_\alpha$ and the $cell_\beta$ and between the $cell_\alpha$ and the MUE is further proposed to exploit. This allows a reduction in the number of cells in the NCL by exclusion of cells, which cannot be accessed right now due to user's location. The proposed Distance-Based Scanning (DBS) algorithm extends work presented in previous section where the knowledge of previous visited cell and principle of obstructed paths between two cells to reduce number of scanning events is exploited. In this section, the proposed enhancement consists in consideration and derivation of the distance between neighboring cells.

The main problem related to the determination of the distance between two cells and among the cells and the UE consists in accuracy of localization of the user and the SCeNBs. Localization by using information from the network (e.g., Angle of Arrival, Time of Arrival, etc.) or satellite navigation systems (e.g., GPS, GLONASS, etc.) can be very inaccurate in urban areas or even impossible indoor due to unavailable signal. Another problem of these techniques is relatively high energy consumption if those systems are integrated in mobile devices such as smart phones [103].

In terms of SCeNB, the location of microcells and picocells is usually known very precisely as those are deployed by operators. However, localization accuracy of HeNBs is limited since the HeNBs are deployed by the users. Moreover, user's movement is restricted to street or maps with a certain level of volatility. Therefore, the determination of mutual distance among SCeNBs and among SCeNBs and users based on real position is not applicable globally. To enable utilization of the proposal in general scenario when position of objects is not known accurately, only relative distance is exploited. To determine the relative positions of the cells, the statistical observation of users' movements is used. The relative position of the cells is determined based on the user's average speed v_{avg} and time $t_{\alpha M\beta}$ that the MUE spends connected to the MeNB when passes from $cell_\alpha$ to $cell_\beta$.

The relative distance is represented in graphs, based on Figure 31, by weighted edges as depicted in Figure 31. Individual neighbors of the MeNB are represented in the graph by vertexes and weights assigned to the edges. The weights represent the shortest distance between two cells. Note that the distances from $cell_x$ to the $cell_y$ is the same as distance from $cell_y$ to the $cell_x$ if no hysteresis for handover is considered (as presented in Figure 31 for clarity purposes). However, in real network as well as in this simulation, the hysteresis is included. Hence, the distances between cells can be different for opposite directions.

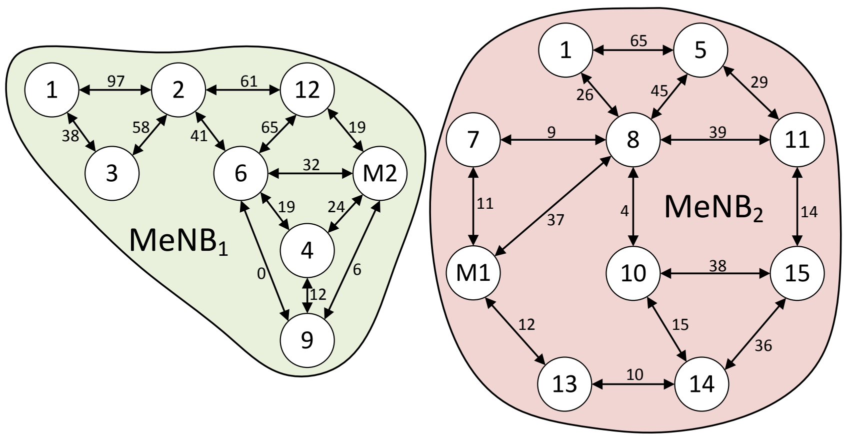


Figure 31: Expression of example network deployment by graph theory with weighted edges

Evaluation of edges can be described for each MeNB by a distance matrix D. For the $MeNB_M$, the distance matrix D_M is defined as:

$$D_M = \begin{pmatrix} d_{11} & \cdots & d_{1\beta} & \cdots & d_{1m} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ d_{\alpha 1} & \cdots & d_{\alpha\beta} & \cdots & d_{\alpha m} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{n\beta} & \cdots & d_{nm} \end{pmatrix} \tag{19}$$

where $\alpha = \{1, 2\ldots, n\}$ and $n = |A_M|$ is the total number of cells from which handover to the $MeNB_M$ can be performed; similarly $\beta = \{1, 2\ldots, m\}$ where $m = |B_M|$ is the total number of cells to which the handover from the $MeNB_M$ can be performed; and $d_{\alpha\beta}$ is the shortest observed distance between the $cell_\alpha$ and the $cell_\beta$. Note that the distance $d_{\alpha\beta}$ may not be the same as distance $d_{\alpha\beta}$. In general, the distance $d_{\alpha\beta}$ is calculated as:

$$d_{\alpha\beta} = v_{avg} \cdot t_{\alpha M\beta} \tag{20}$$

where $t_{\alpha M\beta}$ is the time spent by the MUE connected to the $MeNB_M$ when the MUE passes from the $cell_\alpha$ to the $cell_\beta$; and v_{avg} represents the average speed of the MUE during movement from the $cell_\alpha$ to the $cell_\beta$. The $t_{\alpha M\beta}$ can be expressed as difference between the handover from the $cell_\alpha$ to the $MeNB_M$ ($t_{\alpha M}$) and the time instant of the handover from the $MeNB_M$ to the $cell_\beta$ ($t_{M\beta}$), i.e., $t_{\alpha M\beta} = t_{M\beta} - t_{\alpha M}$.

The main challenge of the proposed algorithm is the detection of UE's speed and estimation of the speed for future movement in the MeNB as it influences efficiency of scanning. For low speed users (pedestrians), algorithm of speed estimation based on correlation coefficients of OFDM system as described in [99] and further improved in [100] can be exploited. This method shows average error of speed estimation less than 2 % for pedestrians, which is more than sufficient for proposed algorithm. For medium or high speed users in vehicles, the assumption of usage of navigation systems such as GPS with even more precise speed estimation can be made.

6.3.1 Distance-based scanning

To facilitate implementation of the proposed scanning to real networks, the self-configuration phase of the algorithm has to be completed before scanning process itself. Distance-based self-configuration phase is outlined in the following subsection. In the second subsection, process of the distance-based scanning is described.

6.3.1.1 Modification of self-configuration for distance-based scanning

The first step after the new MeNB is deployed is self-configuration phase. At the beginning of this phase, the D_M is empty and DNCs of the $MeNB_M$ are not known. The elements of the D_M are set in the following way:

$$d_{\alpha\beta} = \begin{cases} 0 & for \quad \alpha = \beta \\ \infty & otherwise \end{cases} \tag{21}$$

Note that the $d_{\alpha\beta}$ if $\alpha = \beta$ is kept equal to zero all the time as the MUE can turn back anytime and this time cannot be estimated. This, on one hand, lowers efficiency of proposed approach in terms of number of scanned cells, but on the other hand, it avoids missing cell in the NCL.

The self–configuration phase is depicted in Figure 32. After each handover to $MeNB_M$, the timer t_M is launched and previously visited cell $cell_\alpha$ is stored. During the MUE's connection to the $MeNB_M$ in self-configuration phase, the MUEs scan all cells included in NRT with a scanning period of Δt. At the beginning, the NRT can be derived from approximate network information together with sensing algorithm, such as in [37].

As long as the MUE is connected to the $MeNB_M$ the speed of user is measured periodically using algorithms defined in [100] or global navigation systems for users indoor and outdoor, respectively. When the handover from the $MeNB_M$ to the $cell_\beta$ is performed, the timer t_M is frozen and its value is stored in $t_{\alpha M\beta}$. The distance $d_{\alpha\beta\_UE}$ between $cell_\alpha$ and $cell_\beta$ is calculated according (20) by using time $t_{\alpha M\beta}$ together with v_{avg} measured by the UE. The derived $d_{\alpha\beta\_UE}$ is then compared with $d_{\alpha\beta}$ already stored in D_M. If the new calculated value of $d_{\alpha\beta\_UE}$ is lower than the former $d_{\alpha\beta}$, the $d_{\alpha\beta}$ is replaced by $d_{\alpha\beta\_UE}$ so that:

$$d_{\alpha\beta} = \min\left(d_{\alpha\beta}, d_{\alpha\beta\_UE}\right) \tag{22}$$

After performing a sufficient number of handovers, the distance matrix D_M is filled by the shortest distances between distant neighbors and the self-configuration phase is completed. Remaining infinite values of some elements $d_{\alpha\beta}$ indicate that the $cell_\beta$ is not a distant neighbor of $cell_\alpha$, thus transition from the $cell_\alpha$ to the $cell_\beta$ through the $MeNB_M$ is not possible. It means the path between these two cells is obstructed.

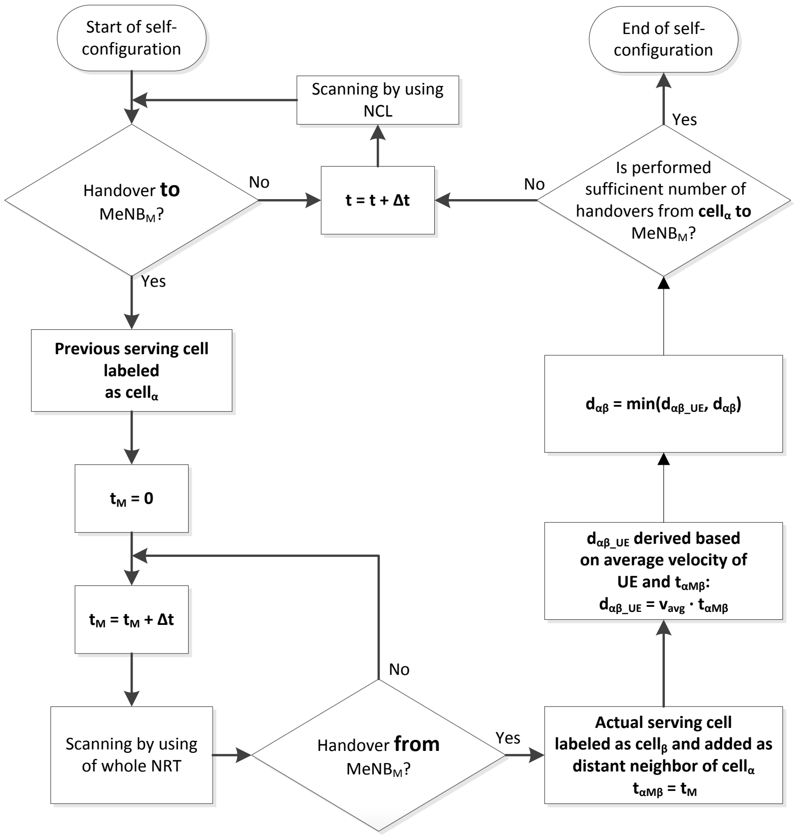


Figure 32: Proposal of self–configuration

Note that the impact of duration of the self-configuration phase has been already investigated in previous section. Based on results, the duration of self-configuration depends on the number of handovers performed to the new installed $MeNB_M$. Although the duration of self-configuration is longer in comparison with conventional algorithms, we have to keep in mind that the self-configuration phase for the $MeNB_M$ is required only once after its first deployment. If any change in neighborhood of the new $MeNB_M$ occurs (for example, a new cell is inserted to the network or a cell is turned off or moved) the $MeNB_M$ is able to react and adapt to this change in self-optimization phase during normal operational state as follows. After plugging any new cell (MeNB or SCeNB) to the vicinity of $MeNB_M$, this new cell is added as the DNC of all cells within $MeNB_M$ range. It means new cell is added to each row of the D_M with value of $d_{\alpha\beta}$ set to 0. If (15) is not fulfilled after a given number of handovers, $d_{\alpha\beta}$ is set to ∞ and this new cell is not considered for scanning by UEs entering the $MeNB_M$ from the $cell_\alpha$. Analogically, the new cell is included as a new row in the D_M of the $MeNB_M$ and elements $d_{\alpha\beta}$ are set to ∞ if (15) is not fulfilled after the predefined number of handovers. If (15) is fulfilled, $d_{\alpha\beta}$ is set according to (20).

After finishing the self-configuration phase, the set of cells for scanning is further managed during DBS.

6.3.1.2 Distance-based scanning process

After finishing the self-configuration, the row α of the D_M contains the shortest distances from $cell_\alpha$ to all neighboring cells of $MeNB_M$. All cells with finite distance are considered to be the DNCs of the $cell_\alpha$ and those are included in the set D_{M_α}:

$$D_{M\_\alpha} = \{d_{\alpha\beta} \in D_M \mid d_{\alpha\beta} < \infty\} \tag{23}$$

If the UE performs handover from the $cell_\alpha$ to the $MeNB_M$, the set D_{M_α} is sent to the UE by the $MeNB_M$. This set represents the list of all cells suitable for the handover denoted as NCL. The NCL also contains the information on the shortest distance to particular neighboring cell. Note that the NCL itself is transmitted also for common approaches. Thus this does not imply any additional signaling. The only additional overhead is introduced by information on the shortest distance between cells. This leads to overhead of several bits (e.g., 10 bits enables reporting of distance up to 1023 m with accuracy of 1 m) per scanning event. The number of scanning events due to proposed algorithm is in order of several events per second (as it is shown later in section that). Therefore, additional overhead is in order of tens of bits per second and can be neglected. Contrary, by reduction of the number of scanning events with respect to existing approaches, the overall overhead due to the scanning can be even lowered by proposed algorithm.

After each handover to the $MeNB_M$, the timer t_M in MUE is launched. Also, the speed of UE is estimated (v_{est}) based on the current and previous speed. For the sake of simplicity, only simple linear extrapolation for the speed prediction is used, i.e.:

$$v_{est}(s) = \frac{1}{p}\sum_{i=1}^{p} v(s-i) \tag{24}$$

where $v_{est}(s)$ is the future estimated speed and p is the number of previous steps taken into account (for evaluation, ten samples are considered). Based on the MUE’s estimated speed v_{est}, the MUE recalculates the distances $d_{\alpha\beta}$ (in the set D_{M_α}) to the minimum time $t_{\alpha\beta}$(in the set T_{M_α}) that is needed to reach individual distant neighbors. The $t_{\alpha\beta}$ is computed in the following way:

$$t_{\alpha\beta} = \frac{d_{\alpha\beta}}{v_{est}} \tag{25}$$

The v_{est} is only a prediction of real average speed v_{real} in the future. Thus, the v_{est} is affected by the error in speed measurement (v'_{meas}) and error in estimation of the future speed (v'_{pre}). The v_{est} is the sum of the real speed and both errors:

$$v_{est} = v_{real} + v_{inac} = v_{real} + v'_{meas} + v'_{pre} \tag{26}$$

Exact determination of v_{real} in the time of handover to the MeNB is not realistic and it can be assumed that $v_{est} \neq v_{real}$. In case the estimated speed $v_{est} < v_{real}$, all minimal achievable time $t_{\alpha\beta}$ (calculated according to (25)) are higher than the real one. This may cause that the MUE arrives to the vicinity of $cell_{\beta}$ before the scanning of this cell is initiated. Then, user cannot connect to the $cell_{\beta}$ and the SCeNBs are underutilized. Contrary, when $v_{est} > v_{real}$, the minimal time $t_{\alpha\beta}$ is lower than the real time spent under $MeNB_M$. Due to the shorter minimal time $t_{\alpha\beta}$, the scanning of neighboring cell is performed too early and can be considered as redundant. From the above two options, the second alternative is acceptable as early scanning does not result into significant decrease in QoS while efficient offloading of the MeNBs by SCeNBs is ensured. To avoid underestimation of v_{est}, a Guard Interval denoted as GI which decreases $t_{\alpha\beta}$ derived by (25) to $t_{\alpha\beta\_GI}$ is considered. Thus, all elements $t_{\alpha\beta}$ from the set T_{M_α} are recalculated to set of minimum times $T_{M\_\alpha\_GI}$ as follows:

$$t_{\alpha\beta\_GI} = t_{\alpha\beta} - GI \tag{27}$$

Usage of the GI ensures that the cells are scanned with a sufficient time reserve before handover and a deterioration of QoS is suppressed. Impact of the GI on the performance is evaluated in the paper.

The main idea of proposed algorithm consists in the fact that during the movement through the $MeNB_M$, the MUE scans only the neighboring cells, which are in proximity of the MUE and which are really accessible. It means the MUE scans only cells with minimal achievable time $t_{\alpha\beta}$ lower than elapsed time t_M spent by the UE in the $MeNB_M$. Therefore, the final set of scanned cells can be expressed as follows:

$$S_{MUE} = \{t_{\alpha\beta\_GI} \in T_{M\_\alpha\_GI} \mid t_{\alpha\beta\_GI} < t_M\} \tag{28}$$

The proposed algorithm for selection of cells to be scanned is summarized in Figure 33.

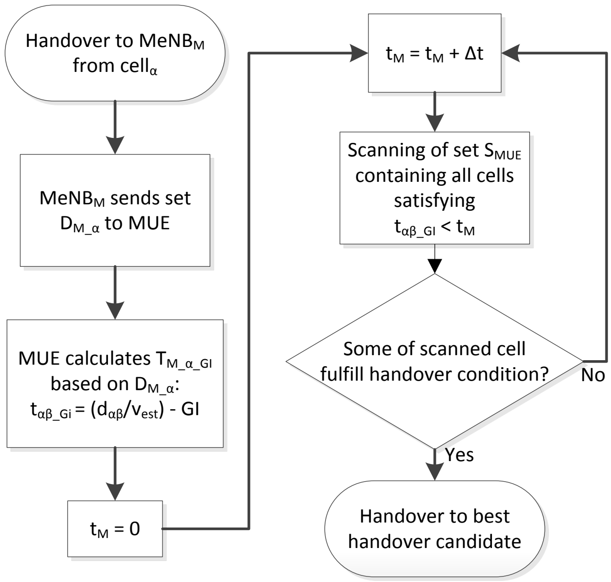


Figure 33: Derivation of set of cells to be scanned

Note that the D_M is continuously managed and updated in the same way as in self-configuration phase during self-optimization phase. It means values of elements $d_{\alpha\beta}$ in D_M are modified if a shorter path is found.

6.3.2 Performance evaluation of distance-based scanning

In this subsection, performance of the proposed algorithm is compared with competitive algorithms. The subsection is divided into three subsections. In the first subsection, competitive algorithms are described. Then, performance metrics are introduced. In the last subsection, simulation results are presented and discussed.

6.3.2.1 Competitive algorithms

Three algorithms are compared with proposed algorithm: Mobility State Estimation-Based Scanning (MSE-BS) [89]; Background Inter-frequency Measurement (BIM) [86], [89]; Obstructed Path (OP) algorithm presented in previous section 6.2. Note that the algorithm OP is also compared with handover history [72] and with sensing algorithm [37] in previous section 6.2. However, for the sake of clarity, the results of these algorithms are not presented here as former proposal OP outperforms all of them as shown in subsection 6.2.3.

First of the compared algorithm, MSE-BS, performs scanning based on the mobility state of the UE [89]. This algorithm selects the cell for scanning based the mobility state. Consequently, only the UEs in the normal state perform scanning of the SCeNBs. In simulations, all UEs are in the normal mobility state as those can fully exploit advantages of the SCeNBs [39]. Therefore, all UEs perform scanning of neighboring cells with an interval of 1 second. With respect to the system model described in subsection 4.2.2, all cells included in B_M (see equation (13)) are scanned.

The second algorithm, BIM, prolongs the scanning period in order to save energy. The prolongation depends on required savings of energy consumption. The scanning is done over the set B_M, however, the scanning interval is changing depending of required energy consumption. In these evaluations, scanning periods Δt = 2, 5, 10, and 20 seconds are considered.

Last, the performance is also compared with the OP algorithm. In this case, only really accessible cells are scanned. Those cells are included in the set B_{M_α} (15).

The proposed distance-based scanning, denoted as DBS, scans only cells included in S_{MUE} defined by (28).

6.3.2.2 Performance metrics

All algorithms are compared by means of average number of scanned cells, prolongation of time in MeNB, utilization of SCeNBs and energy efficiency of scanning.

The average number of scanned cells is expressed as:

$$N_{avg}^{alg} = \frac{\sum_{k=1}^{u} N_k^{alg}}{\sum_{k=1}^{u} T_{M\_k}^{alg} \cdot \Delta t} \qquad (29)$$

where u is the total number of UEs in simulation, Δt is a scanning period, $T_{M\_k}^{alg}$ is total time spent by the k-th UE connected to the MeNBs if scanning algorithm alg is used, and N_k^{alg} is the number of scans performed by the k-th MUE connected to the MeNB during the simulation.

The prolongation of time in MeNBs can be described as follows:

$$\eta_{\Delta t} = \frac{\sum_{k=1}^{u} T_{M\_k}^{BIM_{\Delta t}} - \sum_{k=1}^{u} T_{M\_k}^{\min}}{\sum_{k=1}^{u} T_{M\_k}^{\min}} \cdot 100\% \qquad (30)$$

where $T_{M\_k}^{BIM_{\Delta t}}$ is the total time spent by the k-th UE in the MeNBs for BIM algorithm by using scanning interval Δt and $T_{M\_k}^{\min}$ is a minimum time spent by the k-th UE in the MeNBs by using Δt = 1 s (i.e., by using other compared algorithms).

Utilization of the SCeNB is defined by the next formula:

$$\mu_{\Delta t} = 100 - \left(\frac{\sum_{k=1}^{u} T_{SC\_k}^{\max} - \sum_{k=1}^{u} T_{SC\_k}^{BIM_{\Delta t}}}{\sum_{k=1}^{u} T_{SC\_k}^{\max}} \cdot 100\% \right) \qquad (31)$$

where $T_{SC\_k}^{BIM_{\Delta t}}$ is the total time spent by the *k*-th UE in the MeNBs for BIM algorithm by using scanning interval Δt and $T_{SC\_k}^{\max}$ is a maximum time spent by the *k*-th UE in the MeNBs by using Δt = 1 s (i.e., by using other compared algorithms).

Another compared aspect is the energy consumption due to scanning. The average energy consumption is linearly dependent on the number of scanned cells [89]. Therefore, it is defined as:

$$E_{avg}^{a\lg} = N_{avg}^{a\lg} \cdot \rho = \frac{\sum_{k=1}^{u} N_k^{a\lg}}{\sum_{k=1}^{u} T_{M\_k}^{a\lg} \cdot \Delta t} \cdot \rho \qquad (32)$$

where ρ means the average energy consumption per one scanning of one cell. According to the [89], ρ is set as 3 mWs.

6.3.2.3 Simulation results

In this subsection, results of simulations are presented to provide comparison of the performance with respect to the competitive approaches.

Figure 34 shows the average number of scanned cells per second when the UE is connected to the MeNBs. As can be seen, the MSE-BS algorithm introduces the highest amount of scanning event out of all compared algorithms for all densities of SCeNBs. This algorithm scans all cells to which the handover from MeNBs is possible. Therefore, the number of scanned cells rises with the number of SCeNBs. The BIM algorithm reaches lower average number of scanned cells than the MSE-BS. The number of scanned cells decreases with prolongation of Δt. For example, prolongation of Δt from 10 to 20 s leads to reduction in the average number of scanned cells per second from 2 to 1. However, as in case of the MSE-BS, the number of scanned cells is rising with the density of deployment of SCeNBs. Therefore, the usability of this algorithm is limited by density of SCeNBs.

Contrary to the BIM and MSE-BS, the number of scanned cells is not rising continuously with density of SCeNBs for the OP and for the proposed DBS. For low density of SCeNBs, the number of scanned cells rises with the number of cells. Then, the average number of scanned cells reaches its maximum (at roughly 20 SCeNBs) and decreases for higher density of SCeNBs. The reason is that the paths among cells become more and more obstructed for higher amount of SCeNBs. Thus, the number of real neighboring cells is getting lower. Note that the proposed DBS outperforms the OP by up to 50 % (the average number of scanned cells is reduced from 6 to 3 for 20 SCeNBs). From Figure 34 can be also seen that the DBS algorithm reaches similar results as the BIM with Δt = 2 s and BIM with Δt = 10 s for lower and higher densities of SCeNBs, respectively.

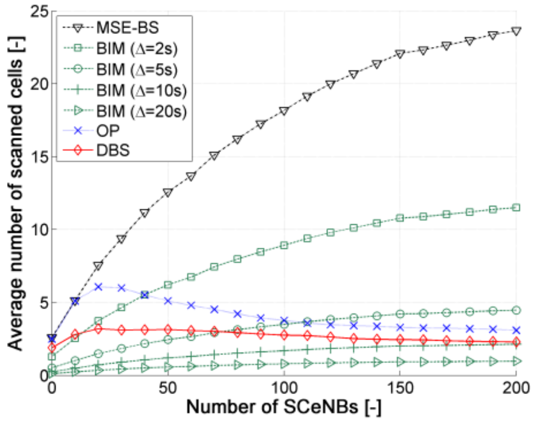


Figure 34: Average number of scanned cells (N_{avg}^{alg}) over density of SCeNBs

As can be seen in Figure 34, the lowest number of scanned cells can be reached by the BIM with long Δ*t*. However, a prolongation of the Δ*t* can lead to the prolongation of the time spent by the UE connected to the MeNB as the neighboring cells cannot be discovered by the UE and handover cannot be performed. A prolongation of the time in MeNBs subsequently leads to the underutilization of the SCeNBs. Therefore, impact of the prolongation of Δ*t* on prolongation of the time in MeNBs and the utilization of SCeNBs is analyzed.

The prolongation of Δ*t* is used only by the BIM algorithm. All other algorithms perform scanning regularly every second (shown by red curve in Figure 35 and in Figure 36). By using Δ*t* = 1 s, prolongation of the time in MeNB is negligible and the users stay minimum time connected to the MeNBs. Contrary, using longer Δ*t* leads to more time spent by the UEs attached to the MeNB. The time in MeNB rises also with density of SCeNBs. For 200 SCeNBs and Δ*t* = 20 s, the time in MeNB is prolonged for more than 16 %.

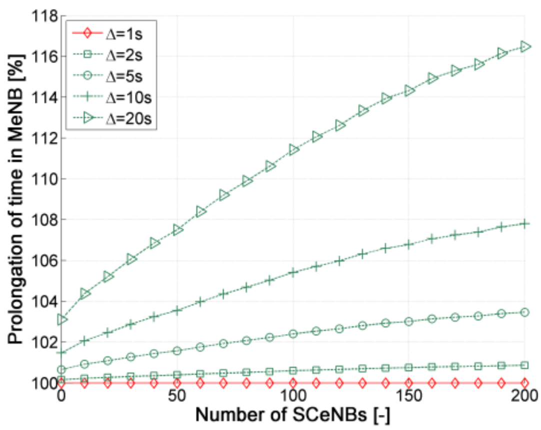


Figure 35: Prolongation of time spent by UEs connected to the MeNBs ($\eta_{\Delta t}$)

Prolongation of the time of connection to MeNB leads, at the same time, to a shortening of the time of connection to the SCeNBs. The main purpose of the SCeNBs in network is to improve QoS for users in its proximity. Therefore, lowering utilization of SCeNBs leads to a loss in their potential to improve network performance. The utilization of SCeNBs in dependence on the scanning period for different densities is depicted in Figure 36. This figure shows the most notable underutilization of SCeNBs for Δt = 20 s and for low densities of SCeNBs. I case of five SCeNBs in scenario, its potential is exploited only at 63.5 %. It means more than one third of capacity of the SCeNBs is not utilized, since the UE is not able to discover the SCeNBs in time. With rising density of the SCeNBs, their utilization rises. Note that sum of the $\eta_{\Delta t}$ and $\mu_{\Delta t}$ is not equal to 100 % since the absolute values of time spent by the UEs in the MeNBs and SCeNBs are different and both are related to $T_{M\_k}^{\min}$ and $T_{SC\_k}^{\max}$.

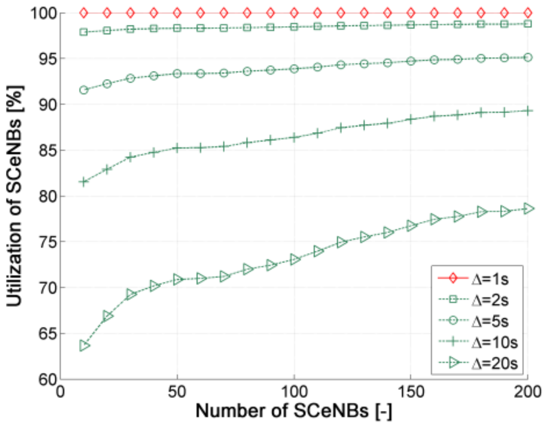
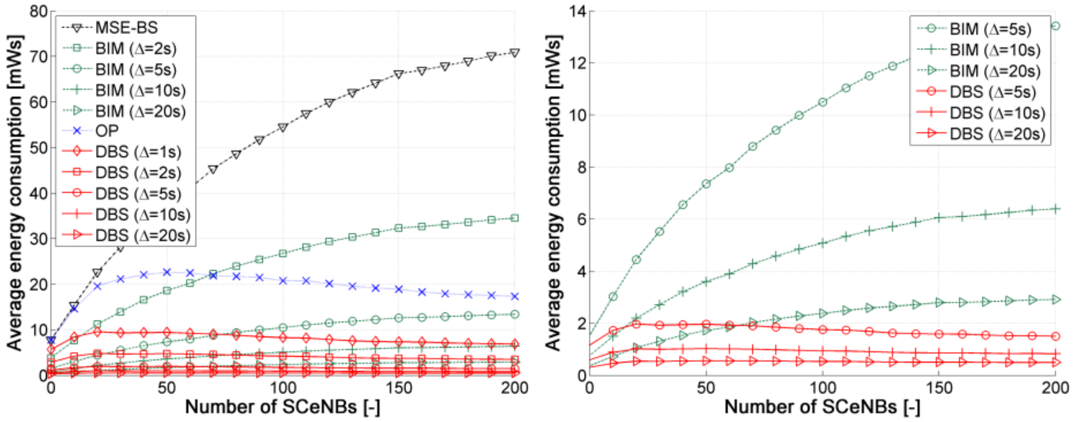


Figure 36: Impact of density of small cells and scanning interval (Δt) on utilization of SCeNBs ($\mu_{\Delta t}$)

In Figure 37, the average energy consumption per second caused by scanning is presented. Figure 37a shows comparison of all algorithms while Figure 37b depicts detailed zoom for algorithms showing low energy consumption. For deeper comparison, the prolongation of scanning period Δt also for proposed DBS is implemented.

As can be seen, the highest energy consumption is reached, as expected, by the MSE-BS algorithm. For 200 SCeNBs, the average energy consumption per second is more than 70 mWs. If the same Δt is used by the BIM and proposed DBS scheme, the energy consumption is reduced for up to 85 % (for Δt = 2 s and 200 SCeNBs).

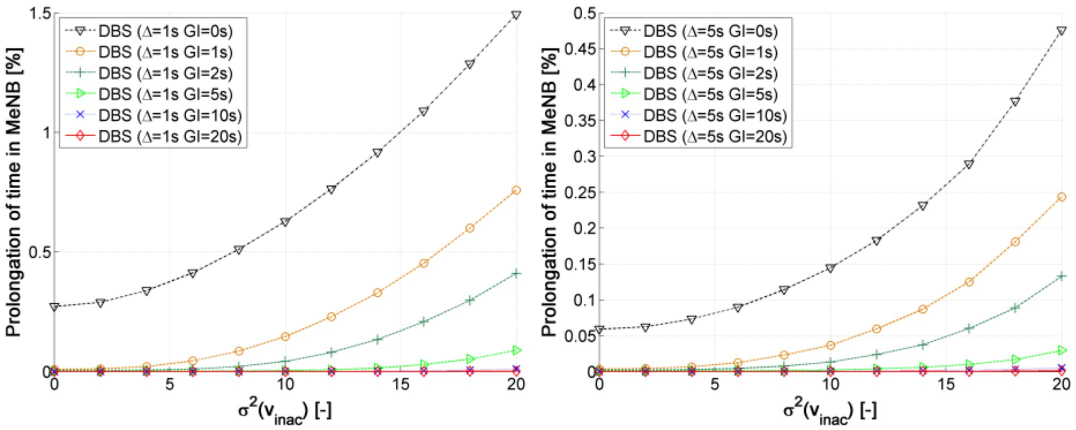
Comparing the DBS with Δt = 1 s with previous proposal OP algorithm, the energy consumption is significantly reduced for all densities of SCeNBs. The reduction is lowered for more than 60 % for most of the densities (except very low density).



(a) (b)

Figure 37: Average energy consumption due to scanning of neighborhood ($E_{avg}^{a\lg}$)

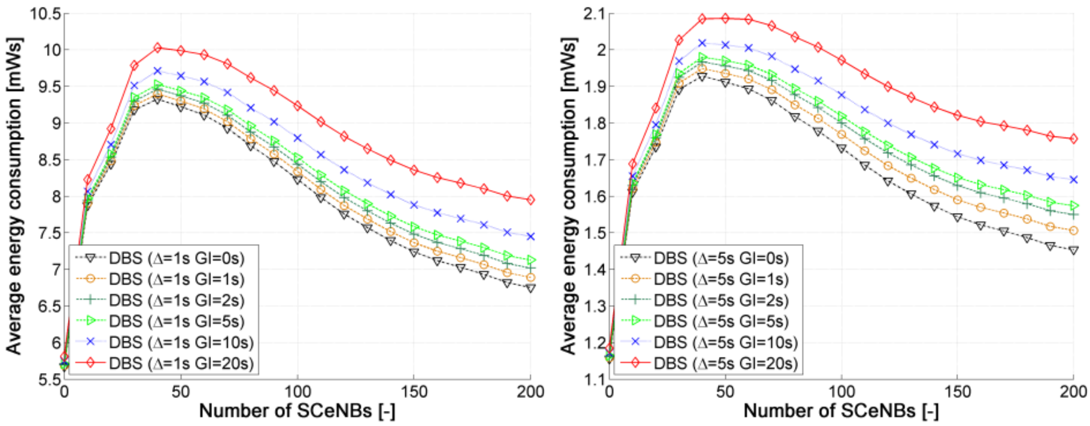
Furthermore, impact of the *GI* on performance of the proposed algorithm is shown in Figure 38. The prolongation of time in MeNB due to the late scanning of neighboring cell is depicted over the variance of inaccuracy of speed determination v_{inac}. The results for scanning periods Δt = 1 s and 5 s are presented in Figure 38a and Figure 38b, respectively. As can be seen, the prolongation of time in MeNB is increasing with $\sigma^2(v_{inac})$. This means the scanning efficiency decreases with inaccuracy of the speed determination. This fact is more notable for shorter *GI*s. For longer *GI*s, $\sigma^2(v_{inac})$ influences the results only negligibly. Note that even low *GI* and high $\sigma^2(v_{inac})$ cause only prolongation up to 1.5 %, which is not significant with respect to results of other algorithms (see Figure 35). The Figure 38 also shows that even the *GI* = 1 s leads to the rapid reduction of prolongation of time in MeNB and nearly no prolongation occurs if the *GI* is set to 5 s disregarding accuracy in speed determination.



(a) (b)

Figure 38: Impact of variance of inaccuracy of speed determination v_{inac} on prolongation of time in MeNB ($\eta_{\Delta t}^{GI}$) for different scanning period Δt of 1 s and 5 s (for 100 SCeNBs)

Figure 38 shows that higher value of *GI* leads to earlier addition of neighboring cells to the set of scanned cells and to elimination of the problem with inaccurate determination of the speed. However, earlier scanning of neighboring cells negatively influences the energy consumption as presented in Figure 39 for Δt = 1 s and 5 s. Both subplots of Figure 39 lead to the conclusion that the average energy consumption rises with the *GI*. However, the difference between energy consumption for the *GI* = 0 s and *GI* = 1 s is negligible (less than 1.5 %). Even extension of the *GI* to 5 s increases the energy consumption only for 5 %. This impact is only marginal with respect to gains presented in Figure 37.



(a) (b)

Figure 39: Impact of GI on average energy consumption for different scanning period Δt of 1 s and 5 s

Based on the results in Figure 38 and in Figure 39, the usage of *GI* = 0 s is not recommended as it prolongs the time in MeNB while the gain in energy saving is not sufficient. On the other hand, the usage of a higher *GI* (i.e., *GI* = 10 or 20 s) leads to an increase in the energy consumption, however, at the same time, the UEs stay connected to the MeNB roughly for the same time as in case of *GI* = 5 s. Therefore, it can be found a compromise between both parameters in setting the *GI* between 1 and 5 s. For these values, the impact on performance is negligible but it can be eliminate even significant inaccuracy of speed determination and estimation.

6.3.3 Discussion of results

Important aspect of user's mobility ensuring of seamless handover is the monitoring of UE's neighborhood to reduce the time and energy consumed by scanning. Since, the SCeNBs are randomly distributed in the network, the standard method of creating the NCL considers only MeNBs are no longer applicable. Solutions proposed for MeNBs cannot be used in the network with the SCeNBs due to limited knowledge of SCeNB's neighborhood and even limited knowledge of HeNBs' position. In this Chapter, new algorithms for creation of NCL of both new installed SCeNBs and new deployed MeNBs is presented. Moreover, new distance-based scanning algorithm considering relative distances between cells is proposed.

At first, an improvement of the procedure for creation of the NCL for the recently deployed SCeNBs is investigated and proposed. The results show that the maximum number of new record to the NCL of the SCeNBs occurs during the first few passes to the street. These new entries cause the highest delays in the few first passes. During further passes of the street, nearly no records are performed and thus the delay significantly drops. The proposed way of NCL management achieves always the lower delay of both investigated methods, i.e., the delay of proposal is equal to minimum of both methods.

Later, new algorithm for creation of the NCL of MeNBs in network with SCeNBs is proposed. The proposed algorithm exploits the knowledge of previously visited cell and the principle of obstructed paths. As the results show, the number of neighboring cells in the NCL of MeNB is maintained at low level even for the MeNB in the environment with the dense deployment of SCeNBs. At the same time, all neighboring cells are discovered and the call drops due to the missing handover target cell do not appear after completion of the self-configuration phase. If also a self-optimization phase is introduced after the self-configuration, new proposed algorithm is still significantly more efficient than the handover history and the sensing as it divides the coverage area of the MeNB into small parts by using the principle of obstructed paths.

Finally, the distance-based scanning algorithm is presented. The proposed DBS algorithm exploits the principle of obstructed paths and the knowledge of previous visited cell together with estimation of the relative distance between cells for selections of cells to be scanned. As the results show, proposed algorithm reaches very low number of scanned cells and low energy consumption while high utilization of SCeNBs is ensured. In terms of number of scanned cells, proposed DBS algorithm outperforms the MSE-BS and OP algorithms for more than 90 % and 60 %, respectively. Energy consumption of MSE-BS can be improved by prolongation of scanning period, i.e., by means of the BIM algorithm. However, this leads to a lower utilization of SCeNBs. This extension can be applied also to proposed DBS scheme. In all cases, proposed algorithm DBS reaches lower energy consumption as well as higher utilization of SCeNBs then the BIM algorithm. To avoid performance degradation of the proposed DBS algorithm due to an inaccuracy of the speed prediction, the *GI* is considered in proposed algorithm. By using the *GI* in range of 1 and 5 seconds, the maximum utilization of SCeNBs is ensured while the energy consumption remains low even for high inaccuracy of the speed prediction.

7. Exploitation of computational resources of SCeNBs

In this Chapter, the algorithm for selection of the computing SCeNBces exploiting both cluster state parameters obtained from all SCeNBces and also parameters of the offloaded task derived from the offloading requests is proposed. In the first section, competitive algorithms applicable for the SCC and proposed algorithm are described. The second section presents performance evaluation of the proposed algorithms and its comparison with existing approaches. In the last section, major conclusions are summarized.

7.1 Selection of computing cells

In this section, algorithms for selection of the computing SCeNBces in the SCC environment are described in two subsections. In the first subsection, common SCeNBce selection algorithms are described while the second subsection introduces the proposed algorithm.

7.1.1 Common algorithms for selection of computing SCeNBces

The SCC environment is a specific type of mobile cloud computing where each SCeNBce is characterized by a set of parameters. These parameters can be split into two groups: transmission path characteristics and computational characteristics. The transmission path characteristics are represented by maximal available throughput and current load of the communication links between UEs and SCeNBces. The computational characteristics are defined by maximal computational power and current computing load of the SCeNBce. All these parameters are collected and stored in the SCM for all SCeNBces in each cluster. Based on these parameters, the SCM selects the SCeNBce(s) for processing of the offloaded tasks.

According to two groups of characteristics (transmission and computation), two basic algorithms for the SCeNBce selection can be considered. Both algorithms focus on the selection of proper SCeNBces, which are able to process incoming task in required handling time (Ψ). The required handling time is the maximum tolerated interval from the beginning of the offloading to the time instant when the results of computation are received by the UE. If the SCeNBce is not able to process the task within Ψ, the user is unsatisfied with offered QoS. The first algorithm, denoted in this paper as *Path*, considers only current parameters of the communication paths for selection of the SCeNBce(s) for computation. Each path between the UE and each SCeNBce can be composed of radio and backhaul segments. If a serving SCeNBce (i.e., the SCeNBce to which the UE is directly connected through radio) is employed, only the radio segment is considered. If other than the serving SCeNBce is selected, both segments (radio and backhaul) are taken into account. Moreover, the backhaul part can be composed of more sub-segments. Single sub-segment of each path is characterized by its maximal available throughput Θ and by the current load of the sub-segment Φ. Available throughput of each sub-segment, $\tau(t)$, is then given as:

$$\tau(t) = \Theta - \Phi(t) \tag{33}$$

The throughput of whole path between the UE and each SCeNBce is given by the lowest current available throughput out of all segments in the path. The available throughput of whole path between the UE and the given SCeNBce is derived as:

$$\tau_P(t) = \min(\tau_1(t), \ldots, \tau_m(t)) \tag{34}$$

where m is the number of sub-segments composing the whole path between the UE and the SCeNBce including the radio as well as backhaul parts (if used). This calculation is performed for all SCeNBces in the cluster. The SCeNBce with the highest $\tau_P(t)$ is selected to process the offloaded task. If parallelization is enabled, the task is split into more parts and the SCeNBce with the highest $\tau_P(t)$ is found for each part of the parallelized task sequentially in the same way.

The second algorithm, denoted as *Comp*, considers only the available computational power for selection of the SCeNBces. Available computing power (A) in time t can be expressed for all SCeNBces as:

$$A(t) = P - L(t) \tag{35}$$

where P is the maximal computational power of the SCeNBce and L is the load of this SCeNBce at time t. However, since the delivery is not immediate, the delay caused by the offloaded task delivery has to be taken into account. The delivery delay can be estimated from known amount of bytes to be transferred from the UE to the SCeNBce ($R_{U\text{-}S}$). As in case of the *Path* algorithm, $\tau_P(t)$ has to be calculated. Based on $\tau_P(t)$ and knowledge of the amount of bytes $R_{U\text{-}S}$ transferred from the UE to the SCeNBce in order to offload the task, the delay caused by delivery of the task from the UE to the SCeNBce ($T_{U\text{-}S}$) can be estimated as:

$$R_{U-S} = \int_{t_i}^{T_{U-S}} \tau_P(t) \;\; => \;\; T_{U-S} \approx \frac{R_{U-S}}{\tau_P(t)} \tag{36}$$

where $T_{U\text{-}S}$ represents the delivery delay between the UE and the SCeNBce. Note that the $T_{U\text{-}S}$ is only estimation of the delivery delay since the throughput of path can vary over the time of delivery. Therefore, $T_{U\text{-}S}$ cannot be calculated exactly in the moment of the offloading request assessment. However, these variations are considered in simulations carried out later in this Chapter.

By using $T_{U\text{-}S}$, the available computing power A at time $t + T_{U\text{-}S}$ (expressed in (35)) can be calculated. As in case of the *Path* algorithm, the $A(t + T_{U\text{-}S})$ is derived for all SCeNBces in cluster and the SCeNBce with the highest computational ability A is selected to compute the offloaded task. If parallelization is enabled, other SCeNBces are included in the way that always the one with the highest $A(t + T_{U\text{-}S})$ is added to the set of computing cells until all parallel sub-tasks are distributed to the SCeNBces.

Although both above-mentioned algorithms are very simple for implementation especially due to the low complexity, the disadvantage of both is an ignorance of other parameters of the tasks. These parameters can be derived from the offloading requests. Consideration of these parameters along with the requirements of users can lead to more efficient selection of the computing SCeNBce(s).

7.1.2 Proposal of application considering algorithm

The proposed algorithm exploits combination of both *Comp* and *Path* algorithms together with knowledge of parameters of the offloaded task for selection of the most suitable SCeNBce for computation. Parameters of the offloaded task are delivered to the SCM in the offloading request. The offloading request contains information such as type of application (e.g., face or speech recognition, etc. [101]), number of bytes to be transferred from the UE to the SCeNBce $R_{U\text{-}S}$, and required handling time Ψ. Based on this information, other parameters can be estimated and the computing SCeNBce(s) can be selected more efficiently.

The proposed Application Considering Algorithm (*ACA*) considers both data transmission as well as computation delay for each SCeNBces in cluster. The delivery delay depends on throughput of individual link over which the data is carried. Therefore, the overall throughput of whole path can be calculated according (33) and (34). Based on $\tau_P(t)$ and knowledge of amount of transferred bytes $R_{U\text{-}S}$, the delay caused by delivery of the task from the UE to the SCeNBce $T_{U\text{-}S}$ can be estimated as in (36).

For calculation of the delay caused by processing of the task by the SCeNBce, available computing power $A(t)$ of the SCeNBce (35) is exploited. Since offloading request delivered to the SCM contains information about the type of application, the SCM is able to estimate the number of instructions to be processed (M) as shown in [101] and in Table 6. Since this estimation can be inaccurate, the long term averaging of the number of instructions M for different types of application can be used for improvement of the estimation accuracy. Based on the estimated M required for the computation of the task, the computation time T_C can be derived as:

$$T_C \approx \frac{M}{A(t + T_{U-S})} = \frac{M}{P - L(t + T_{U-S})} \tag{37}$$

Note that as in case of the *Comp* algorithm, the computational ability A is derived for the future time $t + T_{U\text{-}S}$. Since the SCM manages the assignment of all tasks, it exactly knows the computational load L of all SCeNBces in cluster in every moment. Based on this knowledge, the SCM is able to compute A for future moments.

For expression of the overall handling time (T_{OHT}), delivery delay of results has to be derived. As presented in [101], typical parameters can be observed for each application offloaded to the cloud. Based on these parameters, shown in Table 6, there is possible to assume the amount of bytes of results ($R_{S\text{-}U}$) for particular task according to the type of application listed in the offloading request. Therefore, the results delivery delay $T_{S\text{-}U}$ is derived as:

$$T_{S-U} \approx \frac{R_{S-U}}{\tau_P\left(t+T_{U-S}+T_C\right)} \tag{38}$$

Note that the throughput used for calculation of the results delivery delay $T_{S\text{-}U}$ is postponed to the time $t + T_{U\text{-}S} + T_C$. The inaccuracy of the throughput estimation in time ($t + T_{U\text{-}S} + T_C$) is also included in simulations and reflected in results. The approximated overall handling time of task T_{OHT} can be expressed for each SCeNBce as:

$$T_{OHT} = T_{U-S} + T_C + T_{S-U} \tag{39}$$

The computing SCeNBce(s) are selected according to the T_{OHT} in the way that the SCeNBce with the lowest T_{OHT} performs computation. As in previous cases, if parallelization is employed, the most appropriate SCeNBce for processing of each part is found.

Note that all computed delays are estimated duration of each process. Exact values of all delays cannot be calculated especially due to sharing of all communication paths by more UEs. The capacity of individual paths is not fully under control of the SCM. Therefore, in comparison with load of SCeNBces, the future state of paths cannot be exactly derived. However, in proposed algorithm, the exact value of T_{OHT} is not needed. The values of T_{OHT} are serving only for mutual comparison. Note also that all inaccuracies caused by estimation errors are reflected in the simulation results.

7.2 Performance evaluation of ACA

In this section, performance of the *ACA* in comparison with other algorithms is assessed. This section is divided into four subsections. In the first subsection, compared algorithms are introduced and evaluation metrics are described. Since the impact of satisfaction ratio and deviation of load is heavily dependent on throughput of backhaul, the second and third subsections provide performance evaluation for connection of the SCeNBces to the core network by ADSL and GPON backhauls, respectively. In the forth subsection, discussion of results is presented.

7.2.1 Compared algorithms

For comparison with the proposed *ACA*, two SCeNBce selection algorithms mentioned in subsection 7.1.1 (*Path* and *Comp*) are used. Moreover, since the *ACA* aims not only on ensuring QoS, but also on proper load distribution, the proposal is also compared with two common static load balancing algorithms: Round Robin [104] (in figures denoted as *RR*) and random selection [105] (labeled in figures as *Rand*). When the *RR* or *Rand* are used, the SCeNBces are selected for processing of the task one by one or randomly with uniform distribution, respectively, regardless computational or path parameters, or parameters of the task.

Since the SCC enables parallelization of tasks into account, the number of parallel parts of each task is denoted as parallelization degree (*PD*). In the simulations, *PD* = 1 (no parallelization), 5 and 10 is considered. Each part of the task is of a random size (i.e., random $R_{S\text{-}U}$, M and $R_{U\text{-}S}$) while required handling time Ψ remains the same for all parts as this is related to the whole task. It means the whole task is considered as not completed within Ψ if at least one part of the task does not meet Ψ.

All algorithms are compared by means of two metrics: user satisfaction ratio and normalized standard deviation of load among all SCeNBces in cluster in dependence on mean number of requests arrival per second. The first metric represents QoS, while the second one shows impact of the algorithms on load-balancing. Normalized standard deviation of load $sd(t)$ is expressed as:

$$sd(t) = \frac{\sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}\left(A_i(t) - \overline{A(t)}\right)^2\right)}}{P} \cdot 100\% \qquad (40)$$

where P is the maximal computational power of unloaded SCeNBce, $A_i(t)$ is the current load of the i-th SCeNBce, n is the total number of the SCeNBces and $\overline{A(t)}$ is defined as:

$$\overline{A(t)} = \frac{1}{n}\sum_{i=1}^{n} A_i(t) \qquad (41)$$

In this case, parameter n is equal to 50 SCeNBces and $sd(t)$ is calculated for time t = 1 000 s (i.e., end of incoming period). Note that higher $sd(t)$ corresponds to more unbalanced system.

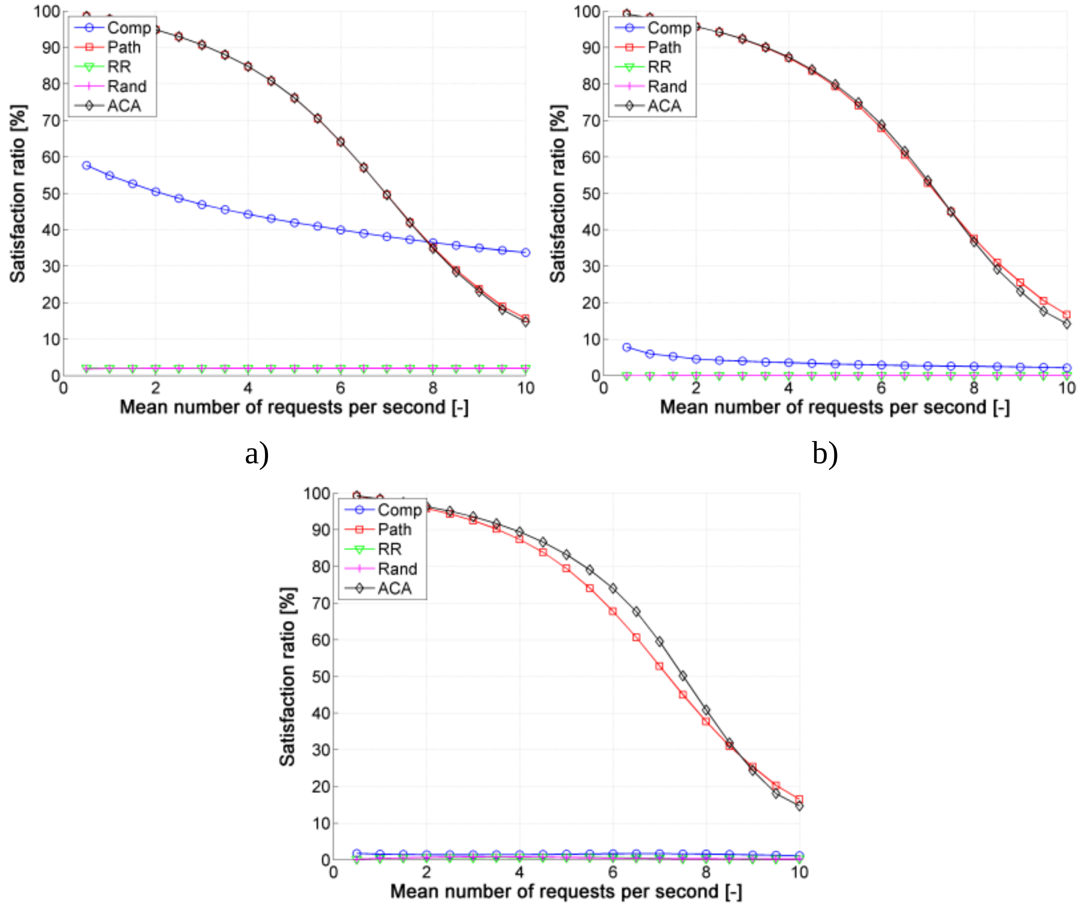
7.2.2 ADSL backhaul

The ADSL represents low throughput connection backhaul. In Figure 40 the satisfaction ratio over the mean number of requests coming to the system per second is presented. Each subplot then shows behavior for different *PD* (no parallelization, 5 parallel parts, and 10 parts in Figure 40a, Figure 40b, and Figure 40c, respectively).

As the results presented in all subplots of Figure 40 show, the satisfaction ratio decreases with increase in frequency of requests coming to the system for the *Path*, *Comp*, and *ACA* algorithms. From Figure 40a can be also seen that the highest satisfaction ratio is reached by the algorithms *ACA* and *Path*. These two algorithms show nearly the same results and outperform all other compared algorithms up to the 8 requests/s. Both *ACA* and *Path* considers path status, which is significant parameter if low quality backhaul (ADSL) is considered and computing load of the SCeNBces is low enough. For frequency of incoming requests higher than 8 requests/s, the

Comp algorithm is able to provide higher satisfaction ratio than the *Path* and *ACA* since the computing time becomes dominate due to overloading of the SCeNBces and tasks are waiting in a queue before computation. The *Comp* algorithm selects always the SCeNBce with the highest available computing power, thus the queue before processing is shorter than in case of other algorithms. Two other algorithms (*RR* and *Rand*) show nearly constant satisfaction ratio of only 2 % for all densities of incoming requests. Such low satisfaction is due to disregarding the tasks' and SCeNBces' characteristics and status.

As can be seen from results presented in Figure 40b and Figure 40c, the parallelization affects the user's satisfaction ratio significantly only in case of the *Comp* algorithm. The parallelization leads to splitting the task into smaller parts. Hence, less bytes are transmitted to each SCeNBce and impact of backhaul quality should be suppressed. Contrary, the task is considered as fulfilled in Ψ only if all parts of the task are processed within Ψ, as mentioned before. Consequently, by splitting the task into more subtasks, the probability that at least one subtask is not processed in time is rising. Finally, the satisfaction ratio for the *Comp* drops under 10 % and under 1 % for $PD = 5$ and $PD = 10$, respectively. Due to the same reason, the decreasing of satisfaction ratio with the rising *PD* can be seen also in case of the *RR* and *Rand*. The parallelization in case of the proposed *ACA* leads to improved performance (from 64 % to 74 % for 6 requests/s). For the *Path* algorithm, the results remain nearly the same despite parallelization.



a) b) c)

Figure 40: Ratio of user's satisfaction in dependence on mean number of requests coming per second for no parallelization (a), splitting of task in 5 parts (b), and 10 parts (c)

Figure 41 shows the normalized standard deviation of load for time t = 1 000 s. In Figure 41a, the lowest standard deviation is reached by algorithms targeting load balancing (*RR* and *Rand*) if requests are coming to the system with a low density (up to 6 requests/s). The deviation of both algorithms is rising with the number of requests per second. The highest deviation for less than 4 requests/s is reached by both algorithms achieving the highest satisfaction ratio, i.e., the *Path* and *ACA*. For a higher number of requests per second, the deviation of *Path* and *ACA* is decreasing. The maximum deviation of 47 % is reached for 3.5 requests/s. The decreasing deviation is caused by the fact that a higher number of tasks in the cluster increase the total load of all SCeNBces and therefore the difference between loads of the SCeNBces is less significant. When 10 requests/s are coming to the system, the *ACA* is able to balance the system and the deviation is equal to zero. It is caused by the fully loaded system and by consideration of the computing load for the task distribution.

By enabling parallelization with *PD* = 5 and *PD* = 10 presented in Figure 41b and Figure 41, the results of *Path* and *ACA* are not changed dramatically in comparison with *PD* = 1 (presented in Figure 41a) since nearly all subtasks are processed in the same SCeNBce. The main difference can be seen for deviation of the *RR* and *Rand*. With a higher *PD*, results of both *RR* and *Rand* algorithms show results closer to the *Path* and *ACA*. The peak in deviation is due to the fact that some SCeNBces are processing tasks while others are still waiting for delivery of the tasks through low throughput backhaul. Then, with additional increase in frequency of requests, the deviation is decreasing. The algorithm *Comp* shows the lower deviation in case of parallelization up to 5 requests/s for *PD* = 5 and up to 6.5 requests/s for *PD* = 10. For higher density of requests, the proposed *ACA* presents lower deviation than *Path*. The lower deviance is caused by more uniform distribution of load by using the *ACA* then *Path*.

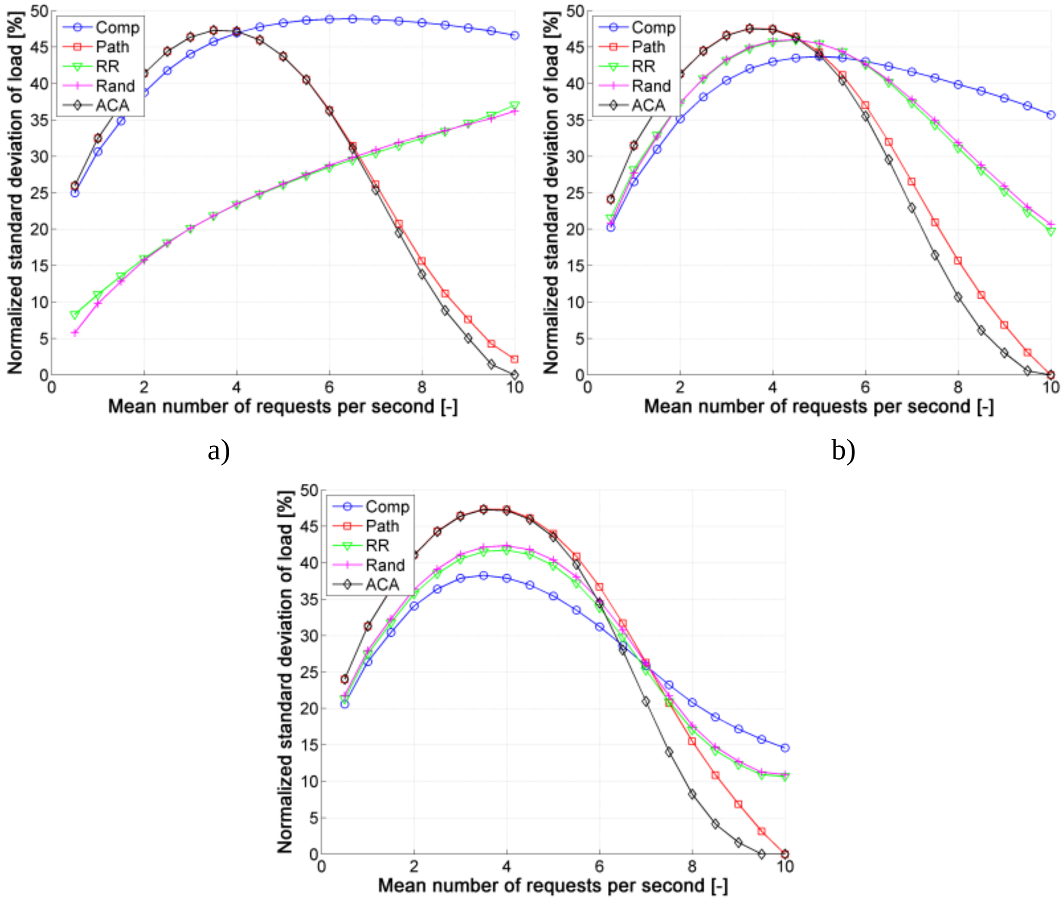


Figure 41: Normalized standard deviation of load in dependence on mean number of requests coming per second for no parallelization (a), splitting of task in 5 parts (b), and 10 parts (c)

7.2.3 GPON backhaul

Performance of the load distributing algorithms for GPON backhaul is presented in Figure 42 and Figure 43. In Figure 42, the satisfaction ratio over the mean number of requests coming to the system per second and for different *PD* is depicted. Contrary to ADSL backhaul (presented in Figure 40) the *Path* algorithm reaches the lowest satisfaction ratio for all *PD*s if GPON is considered. The reason is that GPON enables high throughput. Consequently, the delay due to data transmission becomes less important with respect to the computing delay. Like for ADSL backhaul, the proposed algorithm *ACA* show the highest satisfaction ratio out of all compared algorithms (nearly 100 %) up to the 7 requests/s for all *PD*s. With the further increase in the number of incoming requests per second, the *ACA* shows a decrease in the satisfaction ratio below 20 %. This decrease is caused by limited available resources in heavily loaded system. For a higher frequency of requests, the algorithm *Comp* reaches the highest satisfaction ratio. However, this algorithm is able to satisfy only 96 % of users for low frequency of incoming requests as it does not consider transmission path and the SCeNBce with heavily loaded path can be selected for computation. Other compared algorithms (*RR* and *Rand*) lead to rapid decrease in satisfaction ratio even for low frequency of incoming requests as those consider neither parameters of the offloaded tasks nor status of the SCeNBces and backhauls. For higher *PD*, presented in Figure 42b and Figure 42c, the satisfaction ratio of all algorithms is slightly improved as the computation is distributed among more cells and high quality backhaul is able to distribute task to all cells in a short time, which is negligible with respect to the computation delay.

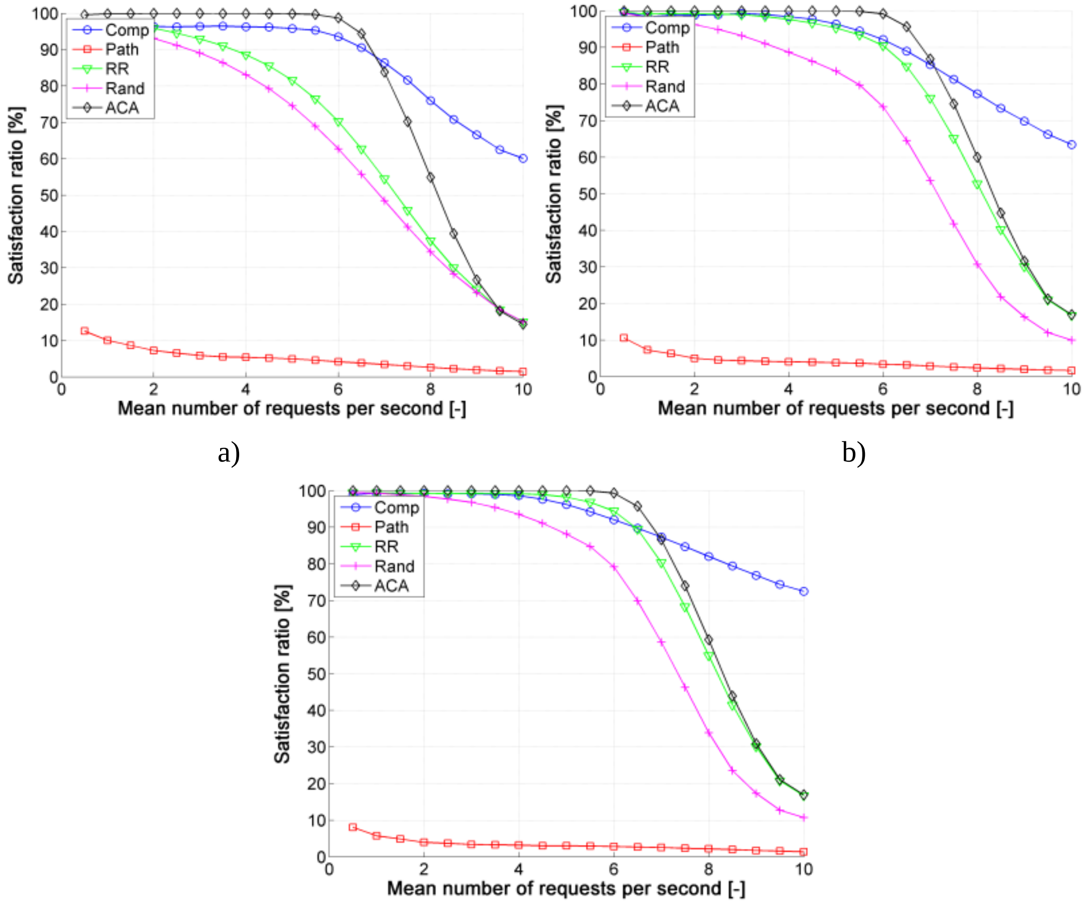
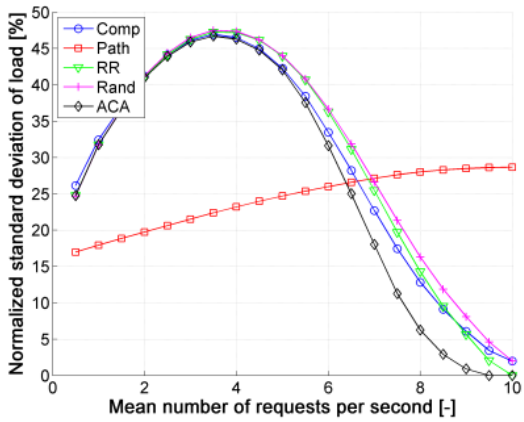
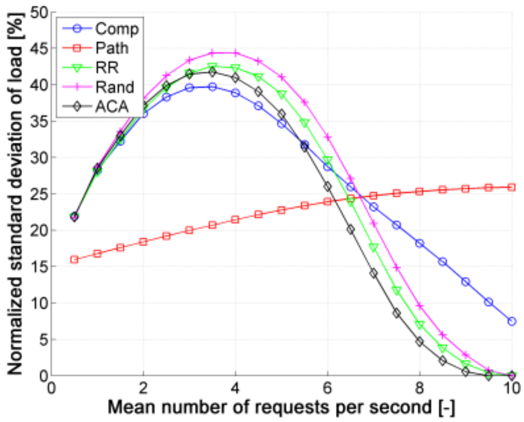


Figure 42: Ratio of user's satisfaction in dependence on mean number of requests coming per second for no parallelization (a), splitting of task in 5 parts (b), and 10 parts (c)

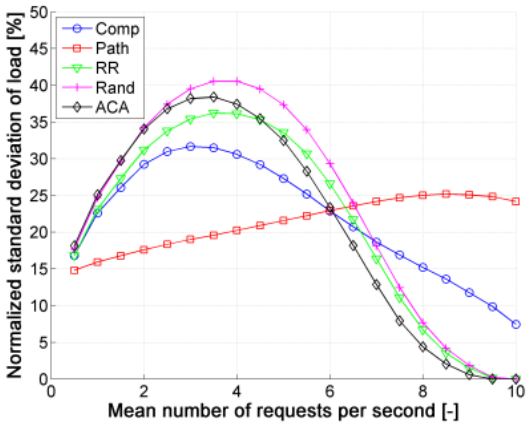
Figure 43 shows the normalized standard deviation of load over all SCeNBces in the cluster. The lowest deviation for low number of requests per second (up to 6 requests/s) is reached by the *Path*. For a higher number of requests per second, the *ACA* provides higher level of load balancing (i.e., the lowest deviation). Behavior of the proposed algorithm is similar like for the ADSL backhaul. By using parallelization, as presented in Figure 43b and Figure 43c, the deviation of the results is lowered due to distribution of the load among cells as described for satisfaction of users.



a)



b)



c)

Figure 43: Normalized standard deviation of load in dependence on mean number of requests coming per second for no parallelization (a), splitting of task in 5 parts (b), and 10 parts (c)

7.2.4 Discussion of results

From above presented results, following conclusions can be derived. First, if a low throughput backhaul (e.g., ADSL) is used, ignorance of the path status leads to dramatic degradation of user's satisfaction. Therefore, the *Path* and *ACA* significantly outperform other competitive algorithms. The *Path* and *ACA* lead to higher deviation of load among cells than load balancing algorithms for low frequency of requests. However, the conventional load balancing algorithms (or *Comp*) are not able to select adequate SCeNBces and leads to nearly full dissatisfaction of users. Therefore, the *Path* and *ACA* algorithms are the most suitable for ADSL backhaul (*ACA* reaches even higher satisfaction if parallelization is enabled).

Second, if a high quality backhaul (e.g., GPON) is used, the algorithms considering computing load of the SCeNBces (*ACA* and *Comp*) outperform other algorithms in terms of the user's satisfaction. The proposed *ACA* is more efficient for low to medium density of users' requests. Then, the *Comp* algorithm is the most efficient from the user's satisfaction point of view. From the load balancing point of view, the *Path* algorithm is the most efficient one for low density of requests. However, this algorithm is not acceptable from the user's satisfaction point of view. For a higher density of users' requests, the proposed *ACA* outperforms other competitive algorithms.

In real networks, a combination of both types of backhauls should be assumed. Therefore, the proposed *ACA* algorithm is the most suitable as it reaches the highest satisfaction of users over the most of possible scenarios.

As the results show, proposed *ACA* outperforms all competitive algorithms in most of the cases in terms of users' satisfaction for both ADSL and GPON backhaul. Moreover from the load balancing point of view, the standard deviation of proposed algorithm is always the same or lower than the load deviation of algorithm, which reaches the similar level of user's satisfaction as the *ACA*. Although the *Path* and *Comp* algorithms are able to outperform the *ACA* in some cases, the *ACA* is the most suitable for realistic scenario in real networks, which is assumed to combine backhauls of various qualities and throughputs.

8. Conclusion

The introduction of SCeNBs into existing wireless cellular network allows to improve the throughput and QoS for users and also to offload MeNBs. However, the deployment of SCeNBs raises also several problems. This thesis has been focused on the problems related do resource allocation caused by the deployment of small cells into existing network.

The first contribution of this thesis is the proposal of algorithm for maximal utilization of communication resources of the SCeNBs. The utilization of communication resources is maximized by prolongation of time spent by users connected to the SCeNBs. At first, the modification of hand-out hysteresis for prolongation of time is assessed. As the simulation results show, the most appropriate algorithm for the prolongation of time spent in SCeNB is the conventional handover decision based on CINR. Therefore, the adjustment of hand-out threshold $CINR_{T,out}$ is used for further prolongation of time in SCeNB. By modification of hand-out threshold $CINR_{T,out}$, the time spent by users in SCeNB can be significantly prolonged in comparison with hand-out hysteresis while the outage probability is lowered. Moreover, by employing this modification, the number of handovers remains at nearly the same level as in case of the conventional handover decision. However, the prolongation of time in SCeNB can lead to lack of signal quality and therefore to low QoS for users. Therefore, the willingness of users to stay connected to SCeNBs for a longer time in exchange for lower connection cost provided via SCeNBs than via MeNBs is considered. As the results show, the users who do not require services with high quality can select lower level $CINR_{T,out}$ for longer time of connection to SCeNBs since the quality of connection is sufficient for its services. In return, the users with lower quality have reduces price of the connection.

Another problem addressed in this thesis is related to management of the NCL of new installed SCeNBs and MeNBs. First, an improvement of the procedure for creation of the NCL for the newly installed SCeNBs is proposed. The configuration of NCL is based on usage of temporary NCL for initial time period until sufficient number of handover is performed. The presented results show that the proposed way of NCL creation achieves always a lower delay than both compared algorithms, since the delay introduced by the proposal is equal to minimum of both algorithms.

Further, new algorithm for creation of the NCL for newly installed MeNBs is proposed as well. The presented algorithm exploits the principle of obstructed paths together with knowledge of previous visited cell. As the results show, the number of neighboring cells in the NCL of MeNB is significantly lower in comparison with conventional algorithms even for the MeNB in the environment with dense deployment of SCeNBs. Moreover, all neighboring cells are discovered by the proposed algorithm and the call drops due to the missing handover target cell do not appear.

To ensure efficient scanning of neighboring cells, the algorithm based on distances between cells is proposed. Distance-based algorithm exploits the principle of obstructed paths and knowledge of previous visited cell together with estimation of the relative distance between cells for selection of proper cells for scanning. Presented results show that the proposed algorithm is able to reach lower number of scanned cells than competitive algorithms and also energy consumption is reduced. Concurrently, all cells in close vicinity are scanned and, therefore, a high utilization of SCeNBs is ensured. Further reduction of energy consumption of the proposed algorithm by prolongation of scanning period is also assessed. To avoid performance degradation, of the proposed algorithm due to an inaccuracy of the user's speed prediction, the guard interval is introduced to the proposed algorithm. The guard interval ensures a high utilization of SCeNBs while the energy consumption remains low even for high inaccuracy of the speed prediction.

The thesis also addresses selection of the SCeNBce for computation of users' tasks suitable for the SCC environment. This algorithm exploits information on the state of cluster in combination with information received by the SCM in offloading request for more efficient selection of the computing SCeNBces. The main objective of proposed algorithm is to ensure high satisfaction of users while the load balancing is not heavily affected. As the results show, proposed approach outperforms all competitive algorithms in most of the cases in terms of users' satisfaction for both ADSL and GPON backhauls. Moreover, from the load balancing point of view, the standard deviation of proposed algorithm ACA is always the same or lower than the load deviation of algorithm, which reaches similar level of user's satisfaction as the proposed algorithm.

In future, the concept of connection cost based handover can be extended and modified in order to increase time spent by users in SCeNBs together with minimization of impairment of the connection quality. The metrics to efficiently evaluate users' requirements can be also extended. It means, for example, parameters such as throughput, MeNB offloading requirements, etc. can be taken into account. Simultaneously, the possibility of prediction of the CINR level of SCeNB can be investigated. This could further prolong the time in SCeNBs with minimized negative impact on the outage probability.

In terms of scanning of neighboring cells, self-optimization phase of the proposed algorithm can me improved in order to facilitate automatic adaptation of the set of cells for scanning if the user is attached to the MeNB. The adaptation should be driven by changes in MeNB vicinity. It means the self-optimizing algorithm should be able to automatically adapt content of the NCL based on the new deployed/removed cells. In addition, the NCL should be adapted also specifically for individual users moving with different speed. Also the optimization of scanning procedure based on prediction of users' movement can be proposed.

The prediction of processing time of individual computed tasks can be investigated to more efficient load balancing while the satisfaction of users is ensured. Simultaneously, the distribution of tasks according the type of application can lead to a higher satisfaction of users while the influence to load balancing can be preserved.

Summary of research contributions

The research contributions of this thesis are as follows:

- Advanced mobility model with POIs (Chapter 4)
  - development of advanced mobility model for real simulation of movement of users in urban areas
  - based Manhattan mobility model supplemented with points of interests
  - definition of four types of users; each type of user has different mobility model with different preference of points of interests
  - real user movement is derived based on an analysis of human mobility using real traces [98]
  - **presented in**: Z. Becvar, M. Vondra, P. Mach, "Dynamic Optimization of Neighbor Cell List for Femtocells," In *IEEE Vehicular Technology Conference VTC-Spring 2013*, Dresden, Germany, June 2013
  - **presented in**: Z. Becvar, P. Mach, M. Vondra, "Self-optimizing Neighbor Cell List with Dynamic Threshold for Handover Purposes in Networks with Small Cells," In *Wireless Communications and Mobile Computing*, Dec. 2013

- Maximization of SCeNBs utilization (Chapter 5)
  - maximization of time spent by UE connected to SCeNBs by prolongation of hand-out hysteresis
  - maximization of time spent by UE connected to SCeNBs by lowering of hand-out threshold level
  - analysis of optimum hand-out threshold level over connection cost ratio for different types of users
  - **presented in**: M. Vondra, Z. Becvar, "Connection Cost Based Handover Decision for Offloading Macrocells by Femtocells," In *Wired/Wireless Internet Communication WWIC 2012*, London, UK, Apr. 2012
  - **presented in**: M. Vondra, Z. Becvar, "Handover with Consideration of Connection Cost in Femtocell Networks," In *Wireless Telecommunications Symposium WTS 2012*, Santorini, Greece, June 2012
  - proposals was created within FP7 project FREEDOM (presented also in Deliverable D4.1 Advanced procedures for handover in femtocells)

- Creation of neighbor cell list of new installed SCeNB (Chapter 6)
  - proposal of fast and efficient creation of neighbor cell list of new installed SCeNB

  - evaluation of efficiency of proposed algorithm in comparison with using of empty and full neighbor cell list
  - **presented in**: M. Vondra, Z. Becvar, “Creating the Neighbor Cell List of New-installed Femtocell,” In *Digital Technologies DT 2010*, Zilina, Slovakia, Nov. 2010

- Creation of neighbor cell list of new installed MeNB (Chapter 6)
  - proposal of method for creation of neighbor cell list of new installed MeNB
  - proposed method is based on obstructed paths and knowledge of previous visited cell
  - analysis of efficiency of proposed method by comparison with conventional algorithms
  - **presented in**: M. Vondra, Z. Becvar, “Self-configured Neighbor Cell List of Macro Cells in Network with Small Cells,” In *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications PIMRC 2013*, London, UK, Sep. 2013

- Distance-based scanning (Chapter 6)
  - proposal of algorithm called distance-based scanning
  - proposed algorithm exploits the relative distance between cells and time spent connected to MeNB
  - comparison of proposed algorithm with conventional methods described in literature
  - **submitted to**: M. Vondra, Z. Becvar, “Distance-based Neighborhood Scanning for Handover Purposes in Network with Small Cells,” submitted to *IEEE Transactions on Vehicular Technology* in May 2014

- Application considering algorithm for selection of SCeNBces for computing in small cell cloud environment (Chapter 7)
  - proposal of application considering algorithm exploited combination of both *Comp* and *Path* algorithms together with knowledge of parameters of the offloaded task for selection of the most suitable SCeNBce for computation
  - evaluation of efficiency of proposed algorithm in comparison with basic SCeNBces selection algorithms
  - **presented in**: M. Vondra, Z. Becvar, “Considering Algorithm for Small Cell Cloud,” In *IEEE International Conference on Cloud Networking CloudNet 2014*, Luxemburg, Luxemburg, Oct. 2014
  - **presented in**: M. Vondra, Z. Becvar, “Load Balancing of Computation Resources Allocated to Users in Small Cell Cloud,” In *ITU News*, Dec. 2013
  - proposal was created within FP7 project TROPIC (presented also in Deliverable D5.2 Distributed Cloud Services)

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