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**Department of Applied Electronics and Telecommunications**

**DIPLOMA THESIS**

**Optimization of Next-Generation Networks with  
Focus on LTE**

**Author: Bc. Jan Černý**

**Supervisor: doc. Ing. Jiří Masopust, CSc.**

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## ZADÁNÍ DIPLOMOVÉ PRÁCE

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### Z á s a d y p r o v y p r a c o v á n í :

1. Prostudujte a popište specifikace LTE sítě a popište principy technologií používaných v LTE (OFDMA, MIMO, AMC). Prostudujte a popište jevy ovlivňující kapacitu sítě.
2. Popište způsoby optimalizace LTE sítí pro omezení interferencí.
3. Popište základní funkce komerčně používaného softwaru pro návrh mobilních sítí a uveďte nejpoužívanější programy.
4. Upravte program pro simulaci pokrytí signálem v části GSM sítě pro sítě LTE tak, aby respektoval použití technologií využívaných v moderních sítích. Analyzujte interference mezi vysílači. Vizualizujte vliv interferencí a využití technologií MIMO a AMC na přenosové rychlosti.
5. Zhodnoťte výsledky provedených simulací.

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Vedoucí diplomové práce:

**Doc. Ing. Jiří Masopust, CSc.**

Katedra aplikované elektroniky a telekomunikací

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Doc. Ing. Jiří Hammerbauer, Ph.D.  
děkan



Doc. Dr. Ing. Vjačeslav Georgiev  
vedoucí katedry

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## **Abstract**

This thesis deals with 4th generation standard for mobile telecommunication - Long Term Evolution (LTE), its optimization and planning. LTE comes with new approaches on how to increase speed and stability of wireless data transmission. This paper talks about the most problematic issues caused by interferences in the Next-Generation Networks and their impact on the network's data throughput with focus on the inter-cell interferences. The most important ways to avoid interferences while planning a network are also mentioned. In particular, frequency reuse, power control, scheduling, AMC and MIMO antenna arrays. Also, interference regeneration and cancelation is mentioned and indicators of signal quality in LTE are named. Planning these networks involves many complex tasks, and therefore, advanced software tools are needed. The mostly used are Atoll and ASSET. In the practical part, a MATLAB simulation for optimization of LTE network is presented. The goal behind this simulation is to demonstrate the most important principles of the LTE networks planning and optimizing process and show the interconnection between SINR and data throughput.

## **Keywords**

LTE, Long Term Evolution, Cell Network Planning, Inter-cell Interference, Interference Optimization, Frequency Reuse

## **Abstrakt**

Tato diplomová práce se zabývá sítěmi čtvrté generace - LTE (Long Term Evolution), jejich optimalizací a plánováním. LTE přináší nové způsoby zvýšení rychlosti a stability bezdrátového přenosu dat. Náplní této práce je představit nejzávažnější vlivy interferencí na síť nové generace, jejich dopad na propustnost sítě se zaměřením na mezibuňkové interference. Jsou zde zmíněny nejvýznamnější způsoby zamezení interferencím při plánování sítě, jmenovitě přiřazení frekvencí, řízení výkonu, scheduling, AMC a MIMO anténová pole. Také regenerace a potlačení interferencí je zmíněno a jsou zde uvedeny indikátory kvality signálu v LTE síti. Plánování těchto sítí zahrnuje mnoho složitých úkonů, a proto je zapotřebí pokročilých softwarových nástrojů. Nejpoužívanější z nich jsou Atoll nebo ASSET. V praktické části této práce je popsána simulace pro optimalizaci LTE sítí vytvořená v prostředí MATLAB. Cílem této simulace je názorně ukázat nejdůležitější principy procesu plánování a optimalizace LTE sítí a demonstrovat vztah mezi SINR a datovou propustností sítě.

## **Klíčová slova**

LTE, Long Term Evolution, plánování buňkových sítí, mezibuňkové interference, optimalizace interferencí, znovuvyužívání frekvencí

## **Prohlášení**

Prohlašuji, že jsem tuto diplomovou práci vypracoval samostatně, s použitím odborné literatury a pramenů uvedených v seznamu, který je součástí této diplomové práce.

Dále prohlašuji, že veškerý software, použitý při řešení této diplomové práce, je legální.

.....  
podpis

V Plzni dne 17.5.2017

Jan Černý

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## Abbreviations

3GPP.....	3rd Generation Partnership Project
5G.....	5th Generation Mobile Networks
AFR.....	Adaptive Frequency Reuse
AMC.....	Adaptive Modulation and Coding
ASSET.....	Radio Planning Software
CDMA.....	Code Division Multiple Access
COST-231.....	Empirical path loss mode
CQI.....	Channel Quality Indicator
eNB.....	Evolved Node B
EPC.....	Evolved Packet Core
E-UTRAN.....	Evolved UMTS Terrestrial Radio Access Network
FDD.....	Frequency Division Duplex
GUI.....	Graphical User Interface
HSDPA.....	High-Speed Downlink Packet Access
HSUPA.....	High-Speed Uplink Packet Access
IC.....	Interference Cancellation
IP.....	Internet Protocol
LTE.....	Long Term Evolution
LTE-A.....	Long Term Evolution -Advanced
MIMO.....	Multiple Input Multiple Output
MIMO-MU.....	Multiple Input Multiple Output – Multi-User
MIMO-SU.....	Multiple Input Multiple Output – Single-User
MME.....	Mobility Management Entity
OFDM.....	Orthogonal Frequency Division Multiplexing
OFDMA.....	Orthogonal Frequency Division Multiple Access
PDN.....	Packet Data Network
P-GW.....	PDN Gateway
PRB.....	Physical Resource Block
PUSCH.....	Physical Up-line Shared Channel
QAM.....	Quadrature Amplitude Modulation
QoS.....	Quality of Services
QPSK.....	Quadrature Phase-Shift Keying

RF .....	Radio Frequency
RNP .....	Radio Network Planning
RSRP .....	Reference Signal Received Power
RSRQ.....	Reference Signal Received Quality
SFR.....	Soft Frequency Reuse
SGSN.....	Serving GPRS Support Node
S-GW.....	Serving Gateway
SINC.....	Sinc function
SINR .....	Signal-to-Noise-plus-Interference-Ratio
TDD.....	Time Division Duplex
UE.....	User Equipment
UMB .....	Ultra Mobile Broadband
UMTS .....	Universal Mobile Telecommunication System
VoIP.....	Voice over IP
WIMAX.....	Worldwide Interoperability for Microwave Access

## Symbols

$a$ .....	Beam width parameter [-]
$b$ .....	Directivity parameter [-]
$B$ .....	Bandwidth [Hz]
$C$ .....	Channel capacity [bit/s]
$N$ .....	Noise [W]
$P_0$ .....	Desired received power [dBm]
$PL$ .....	Path loss [dB]
$P_n$ .....	Noise power per PRB [dBm/PRB]
$P_{PUSCH}$ .....	Transmission power [dBm]
$PSD_{RX}$ .....	Spectral power density [dBm/PRB]
$S$ .....	Signal [W]
$\alpha$ .....	Path loss compensation factor [-]
$\theta$ .....	Azimuth (Theta) [°]

# 1 Introduction

Mobile data traffic globally multiplied 14 times between 2010 and 2015 according to Ericsson Mobility Report [1] and it is predicted to grow 12 times more between 2015 and 2021 [2]. Long-term Evolution (LTE) standard is focused on maximum data throughput to follow this trend. It is a very complex system, which involves modern technologies from various fields, starting with optical technology of the backbone network followed by complex electronics for signal processing and control. The technologies applied to maximize the frequency-band-usage efficiency and to increase the data throughput over the air interface are of high importance.

Thanks to its efficiency, LTE became the most widespread standard of 4th generation mobile networks worldwide. It is a more suitable technology for mobile communication networks than WIMAX, mainly due to its compatibility with previous generations, better coverage and higher stability for fast moving subscribers [3]. Other technologies, aspiring to be 4G standards, like for example UMB (Ultra Mobile Broadband) or Flash-OFDM were discontinued [4]. In the end of 2015 there were 480 networks in 157 countries using LTE standard [5] and this number is still growing. The number of LTE subscribers is predicted to double by 2021, when it is expected to outgrow the number of 3G subscribers with 4.3 billion subscriptions [2]. LTE networks will be replaced by 5G networks in the future. The process of standardization of 5th generation should finish in 2018 and first commercial deployment is expected for 2020. However, it will take years for 5G to become the leading standard. Currently, most of the operators are focusing on LTE, its modernization and expansion. In many parts of the world LTE networks are still going to be constructed.

This thesis aims to introduce LTE standard and focuses on interference optimization, technologies improving spectral efficiency and also on network planning. After the introduction of the LTE system, the most important technologies to maximize spectral efficiency, which also help to prevent interferences, are studied. Inter-cell interferences, and interferences in general, lead to malfunction of the network, call drops and decrease of data rates. All these phenomena are highly undesirable. Therefore, searching for new technologies and improving existent ones to cope with interferences, while maintaining

high data rates and capacity of the network, is a subject of high priority. This thesis talks about technologies used to avoid interferences (Adaptive Frequency Reuse, Power Control, MIMO and Beamforming). Interference regeneration and cancelation method is also mentioned. Accurate network planning, together with correct deployment of technologies increasing the spectral efficiency, is the key to achieve an efficient network with desired functionality. Therefore the process of network planning in general is also described and the most commercially used professional software tools are named.

To approximate the process of network planning, a simulation program was created in MATLAB. The program is capable of simulating coverage with empiric models used in LTE planning. The goal is to demonstrate the importance of interference optimization on a visualization of maximum data throughput of the network. This program is described in the practical part of the thesis. The functionalities of the program are presented on an example, where part of an LTE network is optimized using this tool.

Similar approach to this project can be found in master thesis [6], where coverage of LTE femtocells is simulated and interferences with overlay network are examined. This simulation provides a simplified solution for attenuation introduced by buildings. Bachelor thesis [7] uses the Berg's recursive model to predict coverage of microcells. Simulations of signal propagation for mobile networks in MATLAB can also be found in the publication [8] and the LTE principles are closely explained in the publication [9], also using MATLAB programs.

## 2 Aims of this Work

- Introduce LTE network standard
- Name causes of interferences in the network
- Explore technologies used for interference optimization and mitigation
- Visualize some of these methods and the impact of their deployment
- Create simulation in MATLAB to approach network planning process and visualize the impact of previously mentioned technologies.

### 2.1 Task

- Study and describe specification of LTE network and describe principal technologies used in LTE (OFDM, MIMO, AMC). Study and describe phenomena influencing the network.
- Describe LTE networks optimization methods for interference mitigation.
- Describe functionality of commercially used software for mobile network planning and mention most used programs.
- Modify the program used for simulation of signal coverage in part of GSM network for LTE networks so that it respects the deployment of technologies used in modern networks. Analyze interference between the transmitters. Visualize impact of interferences and use of MIMO and AMC on data throughput.
- Evaluate results of conducted simulations.

### 3 Characteristics of LTE Networks

Long-term evolution (LTE) is a cellular technology standard following the third generation UMTS networks. Therefore, LTE is considered 4th generation cellular network (4G). It is based on 3GPP Release 8 from 2008 and it has been further developed. Release 10 is known as LTE-Advanced. It brings, beside other improvements, 8x8 MIMO with 128-QAM in downlink and multiple carrier aggregation of contiguous and non-contiguous available spectrum. The current closed 3GPP release, so called LTE-Advanced Pro, has number 13. Release 13 intensively studies the deployment of massive MIMO up to 64 antennas, usage of beamforming and further reduction of latency of the network. Also aggregation of existing Wi-Fi networks to increase data rate and capacity was introduced. LTE-Advanced Pro is considered a step towards 5G networks. [10]

#### 3.1 Requirements for LTE networks

The LTE standard was made to fulfill the following requirements [12]:

- Flexibility in scalable bandwidth of 1.25 MHz, 2.5 MHz, 5 MHz, 10 MHz and 20 MHz to fill efficiently the available spectrum
- Increase cell edge bit rate
- Reduce latency
- Downlink data rate 100 Mbps for 2x2 MIMO and 20 MHz bandwidth
- Efficient support of various services (VoIP, web-browsing, FTP, Multimedia Streaming)
- MIMO up to 4x2 in downlink and 1x2 in uplink
- 3 to 4 times better spectral efficiency to HSDPA and HSUPA rel. 6
- Maintain connection up to speed 350 km/h
- Full performance coverage up to distance of 5 km
- Only slight degradation up to a distance of 30 km
- Operational coverage up to distance of 100 km
- Minimize costs for implementation and maintenance
- Backwards compatibility with previous standards

## 3.2 LTE Overview

LTE is fully IP based and focuses on delivering multimedia content with improvement of Quality of Services (QoS). The most important technologies allowing LTE to reach high data speed over the air interface within a limited broad band are Orthogonal Frequency Division Multiple Access (OFDMA), Multiple-Input Multiple-Output (MIMO), Adaptive Modulation and Coding (AMC), Power Control and Scheduling. All these technologies strongly interact with each other. The result is a network with maximum data throughput from 100 Mbit/s to 1 Gbit/s depending on the network setup, available bandwidth and supported coding scheme. Very important, especially for real time services, is reduced latency. LTE implements VoIP (Voice over IP). LTE networks are backwards compatible with existing technologies and supports inter-system handover both ways. [11]

## 3.3 LTE Network Architecture

Mobile phones and other types of user equipment (UE) communicate with base stations (eNB) over the air interface. UE together with eNBs forms Evolved UMTS Terrestrial Radio Access Network (E-UTRAN). The eNBs are connected to each other over the X2 interface for mutual communication regarding handovers, load and interferences. They are also connected to the Evolved Packet Core through the S1 interface. This interface ensures the downlink and uplink for the users and network signalization. All the data and voice traffic is routed through the network in form of IP packages. [11]

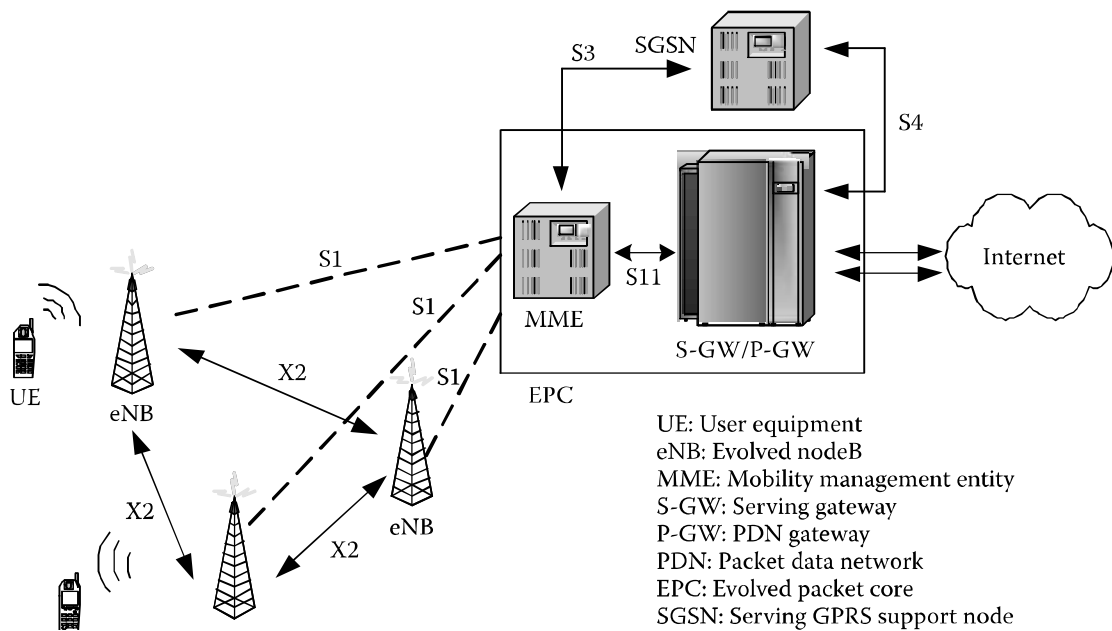


Figure 3.1 LTE network architecture [11]

- User Equipment (UE) is any device connected to an eNB through a RF link
- Evolved NodeB (eNB) ensures communication with UE, routing of subscriber's data and scheduling with resource management of the network.
- Mobility Management Entity (MME) is tracking the position of UEs. Is responsible for the negotiation of handover with other MME. MME ensures authentication of UEs and security. MME is connected to the S-GW through S11 interface
- Serving Gateway (S-GW) handles eNB handovers, billing of subscribers and implements QoS
- PDN Gateway (P-GW) is connected to the Internet. P-GW is responsible for packet filtering and IP address allocation.
- Evolved Packet Core (EPC) is an umbrella title for MME, S-GW and P-GW.

The E-UTRAN structure follows the legacy network architecture of 3G networks but implements some significant improvements. Evolved NodeBs ensure not only the function of base stations, but also the function of the Radio Network Controller. Detailed characteristics of each part of the network are presented in 3GPP specifications [10].



## 4 Interference Optimization in LTE Networks

Interference mitigation has always been an important topic in cellular systems, but LTE brings some new challenges. In order to maximize the data rate, generally the whole frequency spectrum available for the network is assigned to each cell of the network. This results in higher interferences around cell borders. Also, cell density increases especially in highly populated areas. Higher cell density improves the capacity of the network and reduces power requirements, but on the other side, higher cell density results in wider area of high interferences around the cells borders. In addition to that, LTE networks require higher SNIR than any previous standard. For the optimal functionality, LTE network requires SNIR higher than 20 dB [13].

Also, LTE networks often operate on a side of other systems providing 3G, 2G or terrestrial TV broadcasting, etc., causing inter-system interferences. This thesis will mainly talk about inter-cell interferences. However, some of the mentioned techniques can also be applied on inter-system interferences.

### 4.1 Orthogonal Frequency Division Multiple Access (OFDMA)

Data transmission over the air interface is based on the Orthogonal Frequency Division Multiplexing (OFDM). OFDM divides frequency spectrum into multiple closely spaced orthogonal sub-carriers.

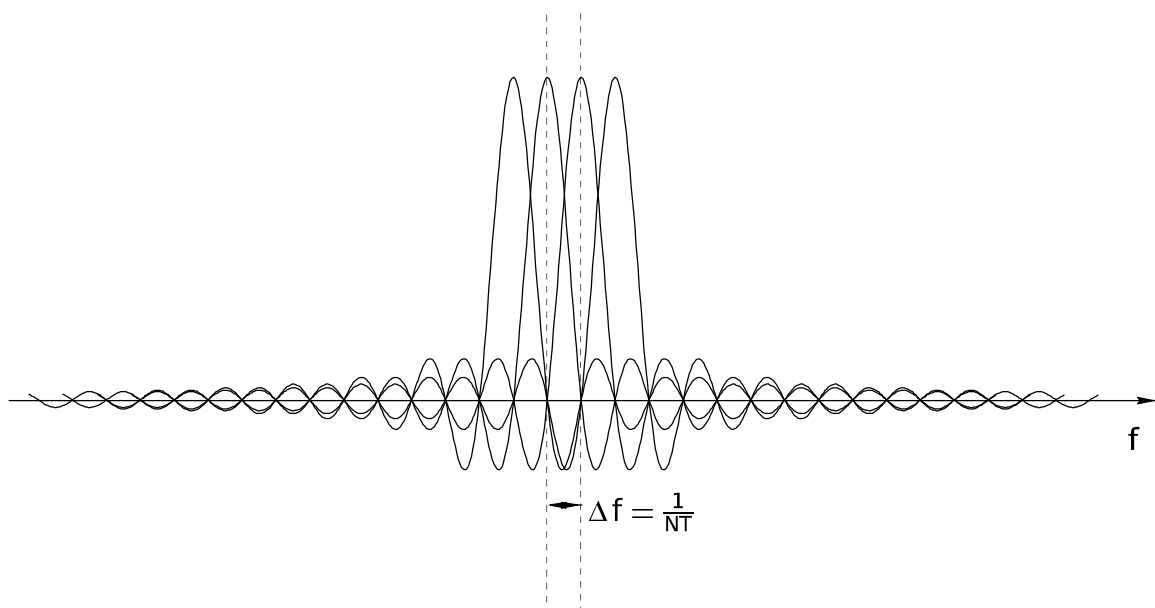


Figure 4.1 OFDM in frequency spectrum

Every single subcarrier can have much lower symbol rate than one carrier would have while occupying the whole band. This efficiently eliminates the effects of multi-path. Reflected signals do not interfere with the next symbol, because all the reflected signals arrive during one symbol duration. To avoid any inter-symbol interference, the cyclic prefix is implemented before every symbol. The symbols on each carrier have rectangular character which results in SINC functions in frequency domain. To ensure no inter-carrier interference, those carriers must be spaced in a way that the center of each carrier matches with the zeros of all other subcarriers. This means that the subcarriers can be closely spaced taking good advantage of the frequency spectrum. In LTE the spacing is 15 kHz.

Each subcarrier is modulated by QPSK, 16-QAM or 64-QAM and must be sampled on the exact central frequency. The spacing frequency and the frequency of sampling must be accurate. Therefore, OFDM is susceptible to frequency errors caused for example, by local oscillator offset or Doppler shift.

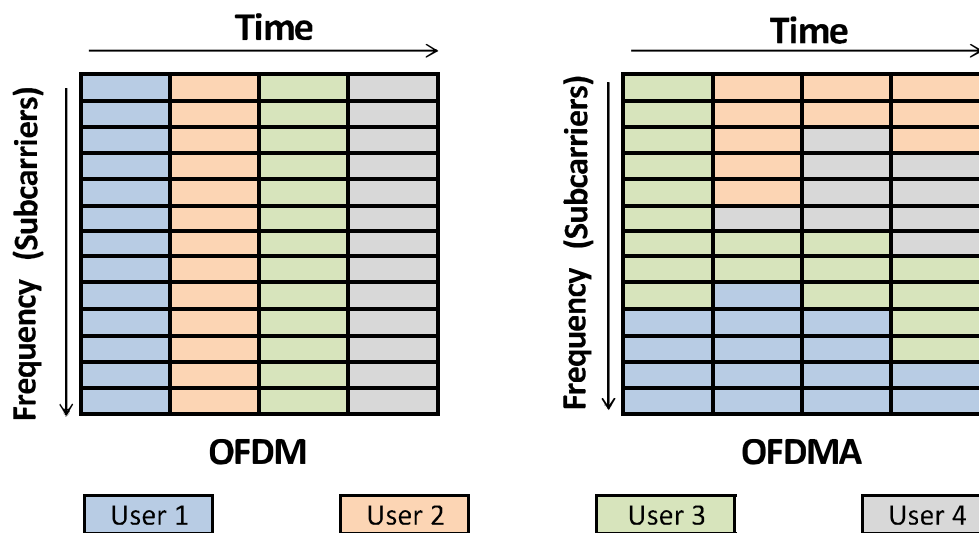


Figure 4.2 This picture shows extension of OFDM, OFDMA. OFDMA assigns carriers to users dynamically, following their current need of bandwidth.

For the purpose of a network with many subscribers, who are accessing different content or service at the same time, the subcarriers are dynamically assigned to the subscribers according to their requirements and the overall traffic within the cell. The minimal portion of subcarriers assigned to one user is called Physical Resource Block (PRB) and consists of 12 subcarriers for 0.5 ms in duration. This period of time corresponds to 6 or 7 OFDM symbols regarding length of implemented cyclic prefix. This extension of OFDM called Orthogonal Frequency Division Multiple Access (OFDMA) is

used in LTE for downlink. For uplink, a Single Carrier Frequency Division Multiple Access (SC-FDMA) was chosen due to its better power efficiency which makes it more suitable for use in mobile devices. [14]

## 4.2 Frequency Reuse

Original 2G cell networks were using frequency reuse patterns where cells had a pre-assigned portion of available frequency spectrum. This frequency band would only be used in spatially distant cells following a reuse pattern [15]. This approach, sometimes referred as Hard Frequency Reuse, was chosen for its simplicity and efficiency considering the request for stable voice service. However, it is not the most suitable technique regarding spectral efficiency, as shown in [16]. To satisfy the increasing demand of mobile data, Next Generation Networks required a different approach. To achieve higher maximum data rate, the Shannon–Hartley theorem (4.1) suggests widening the frequency band.

$$C = B \log_2 \left( 1 + \frac{S}{N} \right) \text{ [bit/s]} \quad (4.1)$$

That is achieved by assigning the whole frequency spectrum to each cell using Full Frequency Reuse (Figure 4.3 b and Figure 4.4 b). This inevitably results in higher inter-cell interferences. The achievement of high data rates inside the cell is ruined by high inter-cell interferences and low quality of reception in the cell-border areas.

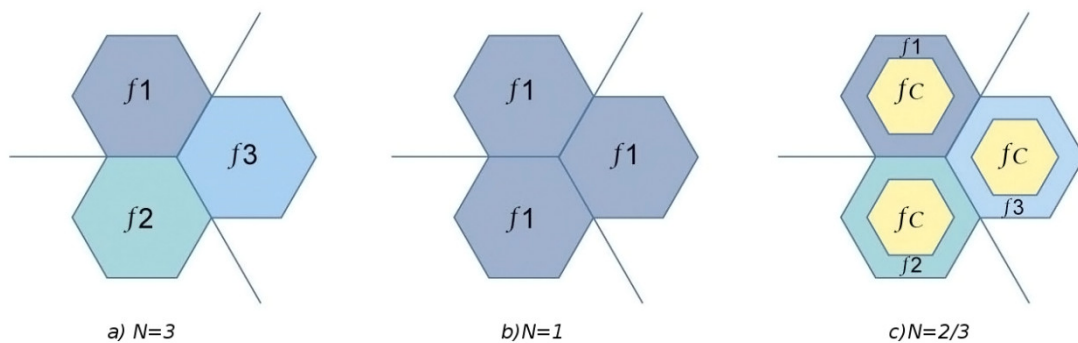


Figure 4.3 Frequency reuse in special diagram: a) Hard Frequency Reuse b) Full Frequency Reuse c) Soft Frequency Reuse [17]

This is the reason why Soft Frequency Reuse (SFR) was developed. It means that the whole frequency band is used to cover the center of the cell ensuring maximum data rate.

The problematic areas around cell borders are served by only a part of the frequency band, which is different in each of 3 neighborhood cells. Soft frequency reuse schemes (Figure 4.3 c and Figure 4.4 c) are often used for its efficiency especially in urban areas with high cell density with over lapses and high number of subscribers in problematic areas.

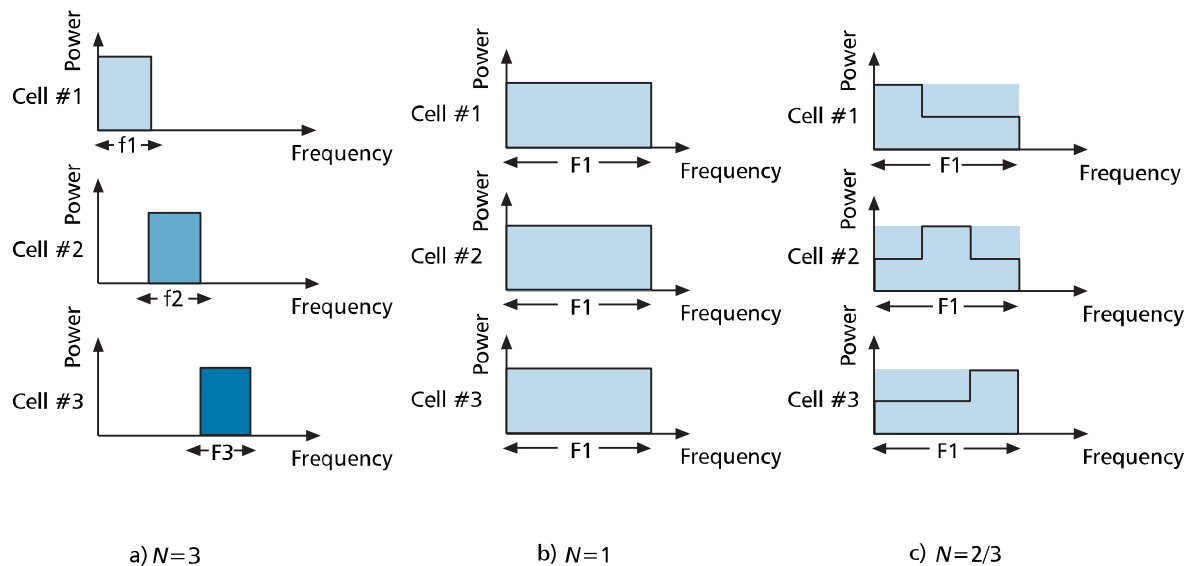


Figure 4.4 Frequency reuse schemes in frequency spectral diagram: a) Hard Frequency Reuse b) Full Frequency Reuse c) Soft Frequency Reuse [18]

Adaptive Frequency Reuse (AFR) is an extension of Soft Frequency Reuse, where the network can dynamically adjust to different situation as if, for example, a cell is in mode with frequency reuse  $N=1$  (Figure 4.3 b and Figure 4.4 b). When eNB receives information about UEs located near the cell borders with low SNR on the downlink, it changes the frequency reuse scheme to a similar to the presented soft frequency reuse and gives information about it to neighborhood cells to do the same. This approach requires inter-cell communication and it is closely interconnected with scheduling process. Deployment of AFR can increase SNIR levels in the network about up to 10 dB. [18]

### 4.3 Power Control

Power control techniques have been developed since the early generations of cell networks to save energy and prolong the battery life of the mobile devices, but mainly to prevent interferences. In LTE, there are no intra-cell interferences due to orthogonal character of used OFDM-based schemes. Nevertheless, inter-cell interferences are still present and in LTE they are more critical than before, as it was previously explained.

### 4.3.1 Opened and Closed Loop Power Control

There are two ways how to determine the transmission power of the UE. The first is called Open Loop Power Control. In this scheme, the transmission power is determined based on an algorithm implemented in UE. This algorithm considers various characteristics, mainly the information about the maximum transmission power and path loss of this received reference signal. Open Loop Power Control is used to determine the initial transmission power when the connection between the UE and an eNodeB is initialized. If the UE started to transmit maximum power, it could lead to massive interferences causing call drops and other malfunctions. The second way is called Closed Loop Power Control and it involves a return channel via TPC command providing personalized feedback for each active EU. Closed Loop Power Control is used when the connection between the UE and an eNB is established. The transmission power of the UE is determined by the eNB and the decision is based on the information about the SNIR of the signal. The transmission power level is updated each 20 ms via TPC command.

### 4.3.2 Power Control

The transmission power  $P_{PUSCH}$  (Physical Up-line Shared Channel) is given by the equation (4.2), where  $M$  is the number of used Physical Resource Blocks (PRBs),  $P_0$  is the desired received power density given by network,  $\alpha$  is the path loss compensation factor and  $PL$  is the path loss. If the path loss compensation factor is  $\alpha = 1$ , we talk about full compensation of path loss. The received power from all the UEs in the cell will be the same, unless it is limited by the maximum transmission power.

$$P_{PUSCH} = 10 \log_{10}(M) + P_0 + \alpha \times PL \quad [dBm] \quad (4.2)$$

Spectral power density of this received power is given by equation (4.3), where  $P_n$  is the noise power per PRB and  $SNR_0$  is the target signal-to-noise ratio.

$$PSD_{Rx} = P_0 = P_n + SNR_0 \quad [dBm/PRB] \quad (4.3)$$

However, full compensation is mainly used in non-orthogonal systems, like for example, in CDMA where equal received power helps to remove the near-far problem.

On the other hand, in systems that use orthogonal transmission scheme it is beneficial to use fractional compensation of path loss ( $0 < \alpha < 1$ ). In this case, the spectral power density of this received power is given by equation (4.4).

$$PSD_{Rx} = P_0 + PL (1 - \alpha) \text{ [dBm/PRB]} \quad (4.4)$$

It is apparent that the received power is decreasing with growing path loss. This diminution depends on the path loss compensation factor as it is shown in the Figure 4.5. The knee point is where the UE reaches the maximum transmission power allowed. Position of this point also depends on  $\alpha$ . [11]

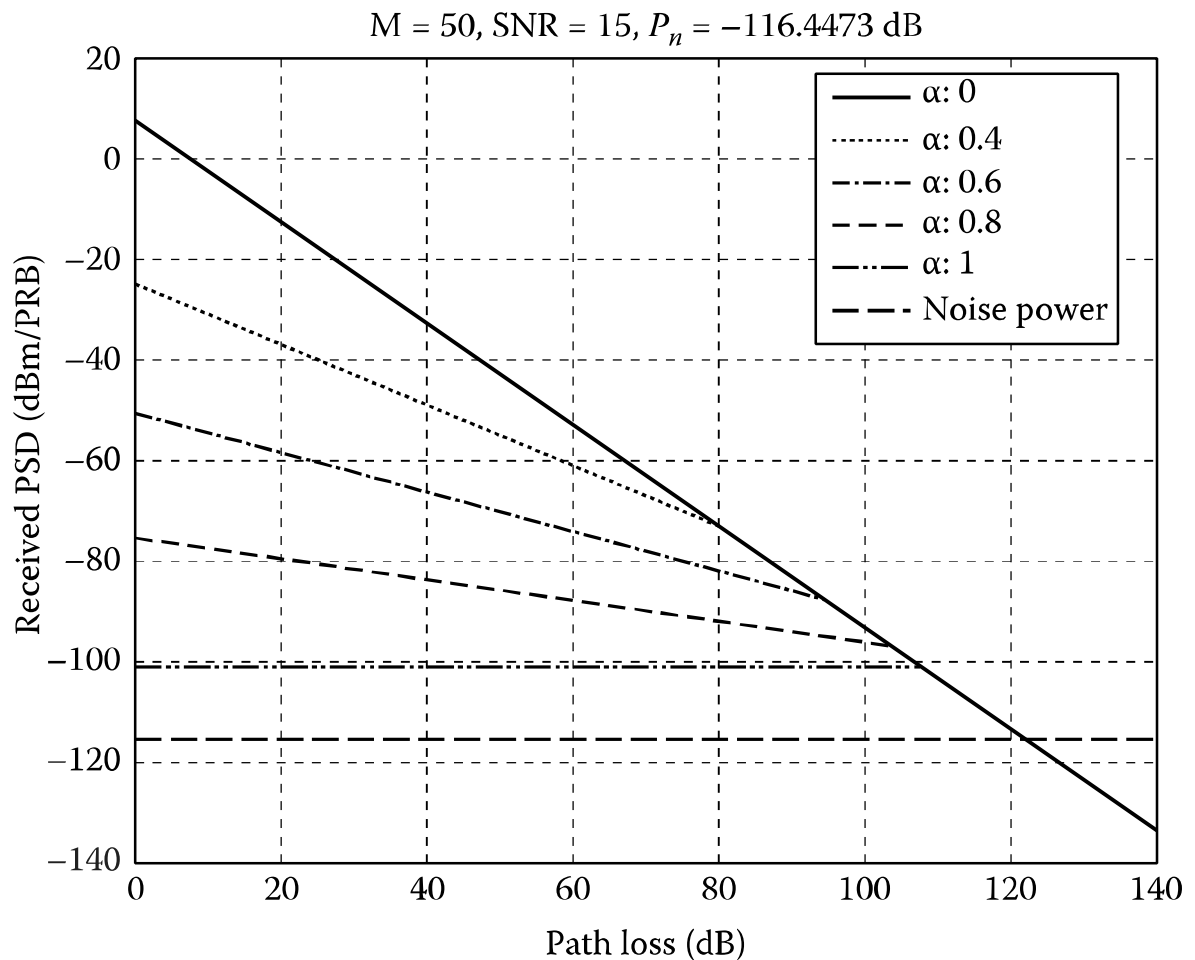


Figure 4.5 Received power as a function of path loss for different values of  $\alpha$  [11]

It has been proved, that fractional power control brings better spectral efficiency and is especially effective in small cells up to 1 km. Fractional power control scheme generally increases aggregate data rate of the cell up to 40% [15] and particularly improves the situation for users on the cell edges. These users reach the maximum transmission power

but do not experience such high interferences like they would, if users in adjacent cells, finding themselves before the knee point, were using the full compensation scheme. [11]

## 4.4 Download Channel Scheduling

Modern systems like LTE do not use power control in the downlink. Instead, they transmit with constant, often maximum power. That results in higher received power and therefore higher data rates. This shortens the connection time necessary to transfer given amount of data. Generated interferences are reduced via scheduling and link adaptation for the downlink channel. Each cell receives information about interferences from neighborhood cells via transmission-power indicator. This indicator provides information about frequency band, where the interferences are occurring. This lets the eNB lower the transmission power for this frequency band or switch to another one and leave this channel free, so it does not cause interferences to any of the adjacent cells.

Scheduling provides efficient distribution of available resources among the active UEs. Several algorithms for scheduling the UEs by the eNBs were proposed. Generally, the more complex algorithms deliver better results. We can divide these algorithms into channel-unaware and channel-aware. In LTE, channel-aware algorithms are used because for wireless networks the knowledge of transmission channel is fundamental to achieve high performance transmission. The quality of transmission is reported using CQI (Channel Quality Indicator). [19]

### 4.4.1 QoS-unaware Strategies

For achieving maximum data throughput it would be logical to schedule those UE, which are reporting favorable transmission conditions. This algorithm can be categorized as QoS-unaware. It ensures maximum aggregate data throughput for the cell, but no fairness to the cell-edge users and other subscribers with low-quality reception. There are several improvements to this algorithm described in [19] that improve fairness for the UEs with inferior signal quality.

### 4.4.2 QoS-aware Strategies

LTE implements QoS which facilitates the implementation of QoS based fairness strategies for scheduling the network resources to the users. Each service has defined the

minimum required performance. The users approaching or below this threshold are scheduled with priority. Special attention must be given to VoIP service, because the maximum acceptable delay for voice is 250 ms. Delay introduced by the network core is about 150 ms, hence, the maximum tolerable delay over the air interface is 100 ms. Therefore, there is a period of time, when VoIP packets have high priority. This period however, must be reduced to the minimum length possible in order to maintain quality of other data related services. [19]

#### 4.5 Multiple-Input Multiple-Output (MIMO)

Theoretically, the easiest way of increasing data speed is to widen the frequency band. Unfortunately, mobile networks providers are always limited by the bandwidth. Therefore, a different approach to increase the speed was needed. Multiple-Input Multiple-Output (MIMO) is one of the solutions. This name stands for the technology where multiple antennas are transmitting multiple different data streams using the same frequency. The antennas are detached therefore each signal has a different path. This is necessary for the receiver to distinguish between the data streams. The rest is a matter of signal processing on the side of the receiver. In LTE, it can be from 2 to 8 streams. In 3GPP release 13, 64 antenna-ports MIMO is studied.

This technology is already implemented in 3G but in LTE the cross-polarization was added. This means that each of two signal waves is polarized in a plane rotated 45 degrees from the horizontal and 90 degree to each other. Cross-polarization helps the receiver distinguish more distorted and attenuated signals. However, MIMO still requires a lot of data processing on the side of receiver. [14] [20]

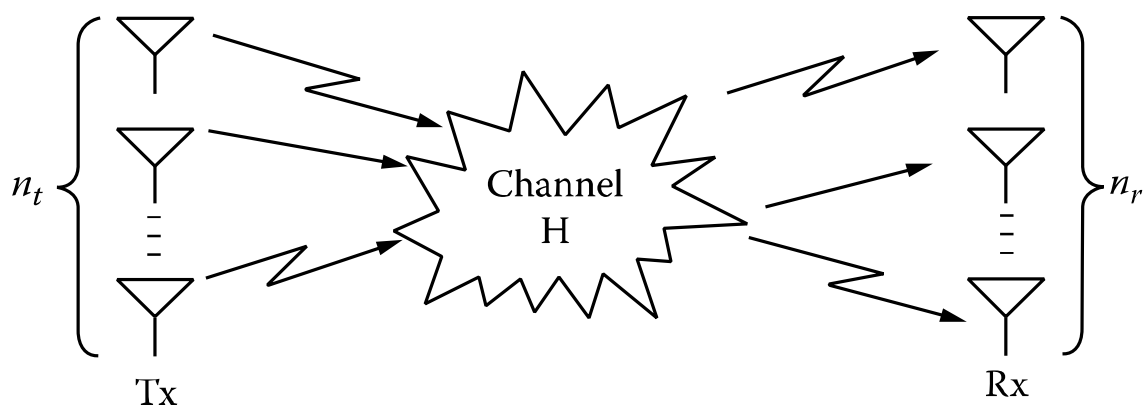


Figure 4.6 MIMO – scenario where multiple antennas are transmitting different data streams using the same carrier but different path of propagation



Usage of MIMO is negotiated between an UE and the eNB. There are different modes of usage of this technology. 3GPP defines eight modes. Mode MIMO-SU is when all the streams are received with one UE. This mode helps to increase data rate for this user. On the other hand, MIMO-MU is when these data streams are received by different UE. This helps to increase the capacity and efficiency of the network. Transit Diversity mode is a slightly different approach. The same data streams are transferred over different MIMO channels. This makes the transmission very resistant and improves the SINR. Complete description of the MIMO transmission modes are defined in 3GPP standard or for example in [21]. The decision of usage of MIMO is closely interconnected with scheduling algorithms.

## 4.6 Beamforming

Beamforming is another way of improving spectral efficiency. With Beamforming, the UE can be directly targeted by an antenna with a directive characteristic with an adjustable angle. This is possible due to the deployment of antenna arrays where the antenna characteristic can be influenced by phase shift of signals arriving to each components of the antenna array (Figure 4.7).

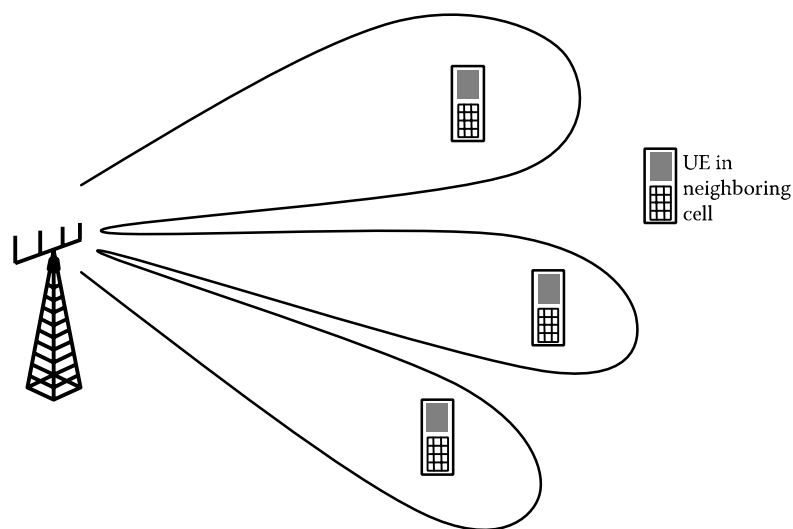


Figure 4.7 Beamforming with antenna array: the UE can be directly targeted by changing the antenna characteristic [11]

The position of the UE is known to the network and therefore can be easily targeted. This technology increases the complexity of the network, but significantly improves the spectral efficiency, because another UE can be served by the same frequency band in the same cell without causing interferences. The same technology can be used also for the

uplink on the side of the eNodeB due to reciprocity of antennas. Directing the beam to the UE increases the gain and decreases the influence of interfering signals arriving from different directions. The deployment of Beamforming is intensively studied in 3GPP release 13. [11] [21]

#### **4.7 Interference Regeneration and Cancellation**

Despite deployment of any previously mentioned techniques, interferences will be still present. One possible way to repair a signal impaired by interferences is to regenerate interfering signal and subtract it from the received signal. The interfering signal is obtained from known reference symbol received with the data stream. This technique obviously requires buffer and complex signal processing. Thus, the Interference Cancellation (IC) is mainly implemented only in the base stations and used for uplink. It helps to fight not only interferences from adjacent cells, but also any other type of interferences.

#### **4.8 Signal Quality Values and Adaptive Modulation and Coding**

Another factor defining the data speed is the number of bits per symbol, which is given by the used modulation. Modulations used in LTE are QPSK, 16-QAM or 64-QAM. LTE advanced is adding 128-QAM and 256-QAM, but these high orders of modulation are currently supported only by premium mobile phones. Adaptive Modulation and Coding (AMC) is responsible for choosing the highest modulation possible with respect to the current channel characteristics. 64-QAM modulation provides 6 bits per symbol, but the transmission becomes more sensitive to noise. Therefore, in case of worse signal conditions, a modulation with lower number of bits per symbol is chosen to keep an acceptable bit error rate. This system ensures maximum data speed in an area of good coverage and stable error-free connection in an area with weaker signal and/or lower Signal-to-Noise-plus-Interference-Ratio (SNIR). This typically happens on the cell edges. [11]

The level of received power is reported by the UE using RSRP (Reference Signal Received Power) number. RSRP depends on the power of received reference signal from the eNodeB and it is defined in a range from -140 dBm to -44 dBm with a step of 1 dBm.

The quality of the signal is expressed by RSRQ (Reference Signal Received Quality) which is a result of formula (4.5), where  $N$  is the number of used resource blocks (PRBs) and RSSI (Received Signal Strength Indicator) is the overall received power by the UE including the interfering signals. RSRQ is defined in the range from -3 dB to -19.5 dB. [22]

$$RSRQ = N \frac{RSRP}{RSSI} \quad (4.5)$$

Tab. 4-1 Relation between RSRP, RSRQ and SINR and meaning of values of these indicators [28]

		RSRP [dBm]	RSRQ [dB]	SINR [dB]
<b>RF Conditions</b>	<b>Excelent</b>	$\geq -80$	$\geq -10$	$\geq 20$
	<b>Good</b>	-80 to -90	-10 to -15	13 to 20
	<b>Mid Cell</b>	-90 to -100	-15 to -20	0 to 100
	<b>Cell Edge</b>	$\leq -100$	$\leq -20$	$\leq 0$

eNodeB chooses the order of modulation according to the CQI (Channel Quality Indicator) number. CQI value varies in the range from 0 to 15. CQI is estimated by the UE based on the SINR conditions and capability of the device to achieve block error rate lower than 10%. CQI=0 means out of range, up to CQI=6 QPSK is used, for CQI values from 7 to 9 16-QAM is used and from CQI=10 64-QAM can be used, if the UE supports it. [23]

## 5 LTE Network Planning

Mobile network is a very complex and therefore expensive technological system. Any mistake made during the process of planning the network results in increase of costs, degradation of the efficiency in the whole building process and network performance. The goal of network planning is to establish a radio network with sufficient coverage and capacity to ensure expected quality of service. All the resources must be used with the maximum efficiency. Therefore, the particular area must be carefully studied in terms of population density, geographical and residential character. Already existing networks must be taken in account. Well planned network should be also prepared for possible future development.

## 5.1 Cell Site Planning

Cell site planning is the whole process of finding the accurate location for the eNodesB sites and defining the size of its cells. One eNodeB typically serves three cells. Cell site planning consists of many different interconnected tasks which can be divided in surveys, coverage planning, capacity planning, and frequency planning. All the tasks of cell site planning are interconnected and one task cannot be carried out without taking in account its impact on other part of the process.

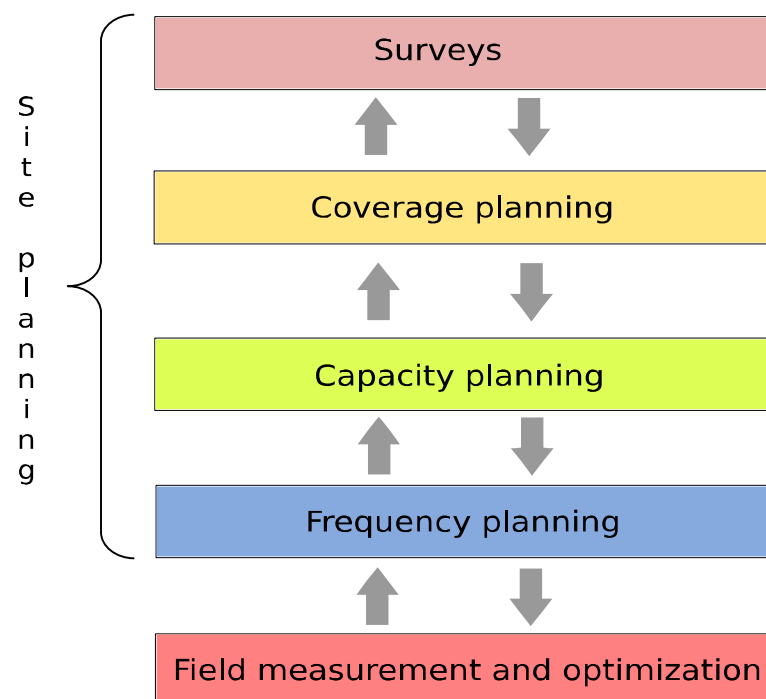


Figure 5.1 Process of Cell Site Planning

## 5.2 Coverage Planning

Coverage planning serves to identify spots with low signal and adjust the position or the power of the eNodeB to efficiently cover the whole desired area. To calculate the coverage, propagation models are used. Propagation models can be either empirical/statistic or deterministic. Empirical propagation models are typically based on the COST-231 model. They give general results about the signal fading as a function of frequency and distance from the eNodeB. Additionally, they are tuned by other additional parameters like general type of environment or relative difference of the antennas height. Deterministic models give more accurate results than empirical. They determine the exact ways of wave propagation paths. To reach these accurate results, the simulation tools

require more specific data about the area and they are more demanding on computing resources. Three-dimensional ray tracing is an example of deterministic model used in LTE planning. To reach higher accuracy when planning, an additional field measurement must be carried out to verify and adjust the results of the simulation. Choice of frequency has also impact on coverage. Higher frequencies have higher path loss and therefore, the maximum size of a cell is smaller. [11]

### 5.3 Capacity Planning

Capacity planning of LTE networks is usually based on measured data obtained from an existing network. The capacity of a cell is limited and one cell can handle only a limited number of subscribers. Therefore, in areas with higher expected traffic (for example a city center) the cell size must be smaller compared to suburban or rural areas.

The arrival of smartphones brought completely new challenges for capacity planning. Smartphones are constantly going from idle state to connected, when applications synchronize with a server. They are also more demanding on data speed and therefore require more bandwidth. [11]

To ensure maximum data speed but also to satisfy maximum users, the bandwidth is assigned dynamically (see 4.1 OFDMA). With more active users in a cell the data speed for one user degrades. To deliver important real time services, as for example voice or video-call in conditions of higher cell traffic, a well-defined Quality of Services protocol must be implemented. With increasing traffic in the network the interference grows, which has also significant impact on capacity. Interferences can be limited with correct frequency planning. [14] [11]

### 5.4 Frequency Planning

3GPP defines various frequency bands in range from 700 MHz to 3800 MHz. It also defines different bands for Frequency Division Duplex (FDD) and for Time Division Duplex (FDD). The used bandwidth can be 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz or 20 MHz. This gives the operators a possibility to implement frequency band available in their area.

Instead of using different frequency carriers in adjacent cells, like for example in GSM, in LTE Full Frequency Reuse scheme can be used. Then the whole frequency band is assigned to each cell. That improves the capacity of each cell but results in higher interference on the borders of the cells. LTE uses scrambling and pseudo-noise codes to distinguish between signals on the same frequency [11]. Still the interferences are present and result in noise which according to the Shannon-Hartley theorem degrades maximum possible data throughput. Therefore, in urban areas with high site density it is recommended to use Soft Frequency Reuse scheme (see 4.2 Frequency Reuse).

## 5.5 Professional Software for Network Planning

To help the engineers with all the complex tasks connected with the network design there are various Radio Network Planning (RNP) software tools. Based on information about the network configuration and characteristics of the environment, the RNP tool provides graphical outputs visualizing coverage, capacity and interference in the network area. RNP software tools must contain characteristics of used network standard and equipment to give applicable results. Therefore, the proper planning software tools must be used for planning of LTE networks. According to [25] and [26] the most popular RNP software is Atoll. Atoll is a multi-technology wireless network design and optimization software tool suitable for many standards including GSM, UMTS and LTE. It supports multi-technology simulation suitable for planning LTE networks along with other standards. It also includes various adjustable propagation models both empirical and deterministic. Atoll also supports various sources of geographical data including popular web map services. Other wide spread software tools are for example ASSET or Pegaplan [27].

There is an example of the coverage calculation in the Figure 5.3. The result shows the achievable data rate which a user can achieve at a certain location in a radio network with a certain probability. This means, that this achievable data rate is calculated for every pixel of the map. [27]

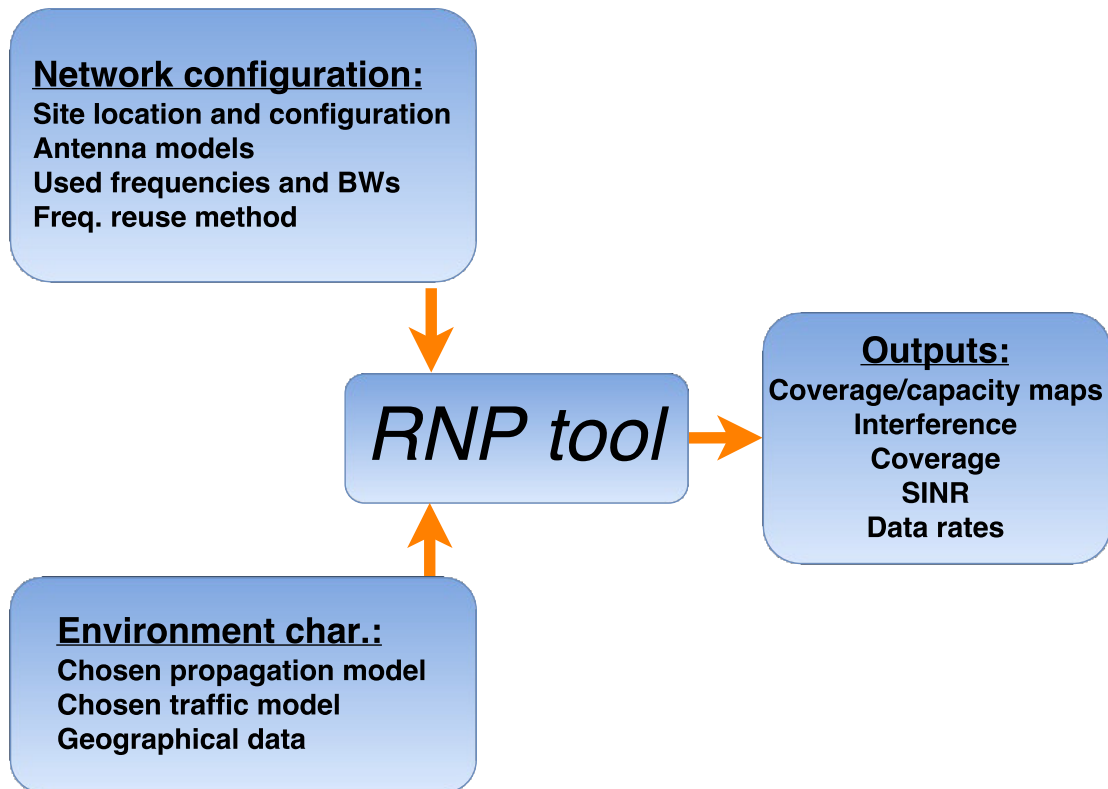


Figure 5.2 Radio Network Planning tool calculates and visualizes its outputs based on introduced data about the network configuration and the particular environment [24]

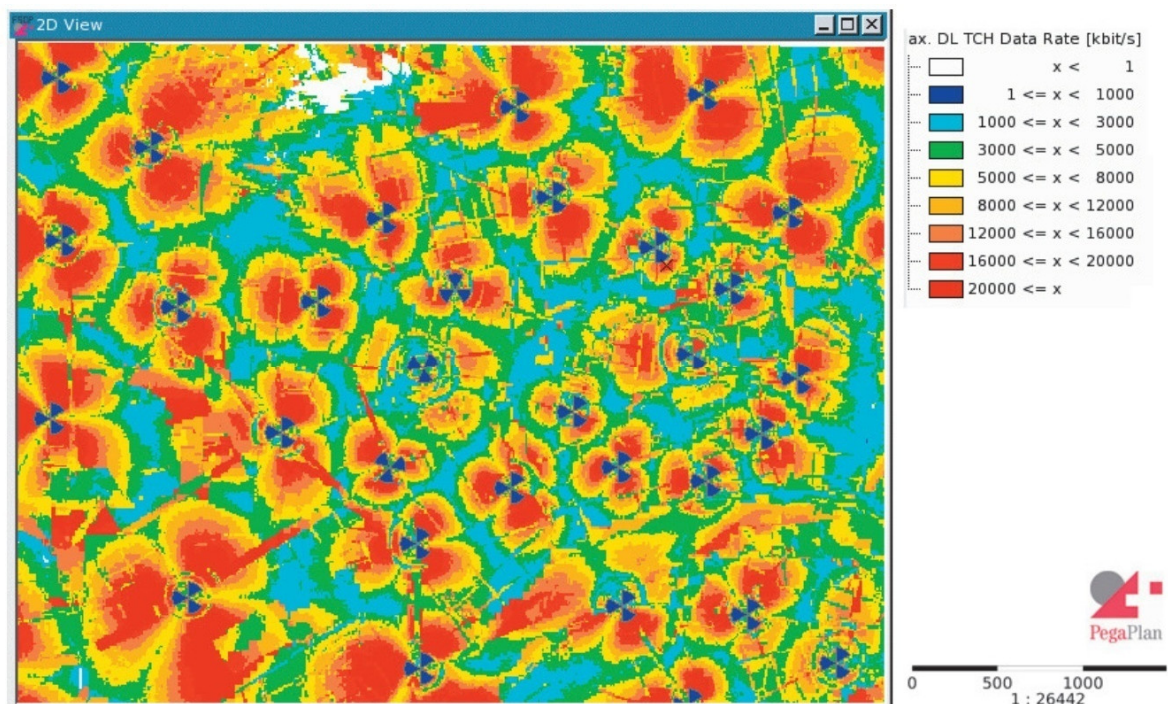


Figure 5.3 Example of coverage map output [27]

## 6 Simulation of LTE Network Optimization

In order to demonstrate and visualize the impact of interferences on the network functionality, a simulation in MATLAB was created. The objective is to take into account propagation loss, MIMO and AMC and show the direct relation between the level of interferences and the network data throughput. Power control technology and scheduling are not implemented. This means that the antennas are assumed to be transmitting maximum power the whole time in the whole assigned frequency spectrum.

### 6.1 Functionality of Simulation Program

In the Figure 6.2 we can see the simulation program with a prepared scenario. The program gets to this stage after loading the jpg file with a map by clicking on “Open file with map”. The size of the scenario can be modified by changing the dimensions. After clicking on “Show Scenario”, the map appears. Positions with information about eNBs are loaded from file posT.txt and shown. The eNBs can be modified, added or deleted by the group of buttons called “Edit Scenario”.

After choosing to add an eNB, user is prompted to right-click to the point where new eNB is supposed to be placed. Then, a query to determine characteristics of antennas appears for each of 3 sectors (Figure 6.1). Different transmitted power, bandwidth and frequency can be assigned to each sector and respective antenna. The same query appears when a sector is edited however, the sectors are edited separately.

When the scenario is prepared, the coverage is calculated either by using COST-231 model or Okumura-Hata model with corrections for city, suburban areas or countryside. Used formulas can be found in [29]. The coverage can be displayed for each point, or only for those with sufficient signal level. Signal stronger than introduced “Threshold” is considered sufficient.

However, quality of the signal is determined by SINR (see 4.8). Therefore, interferences are evaluated in the next step. SINR is calculated as the ratio between the strongest signal and second strongest signal of the same frequency. The final value of SINR for each point is taken for the frequency with highest SINR.



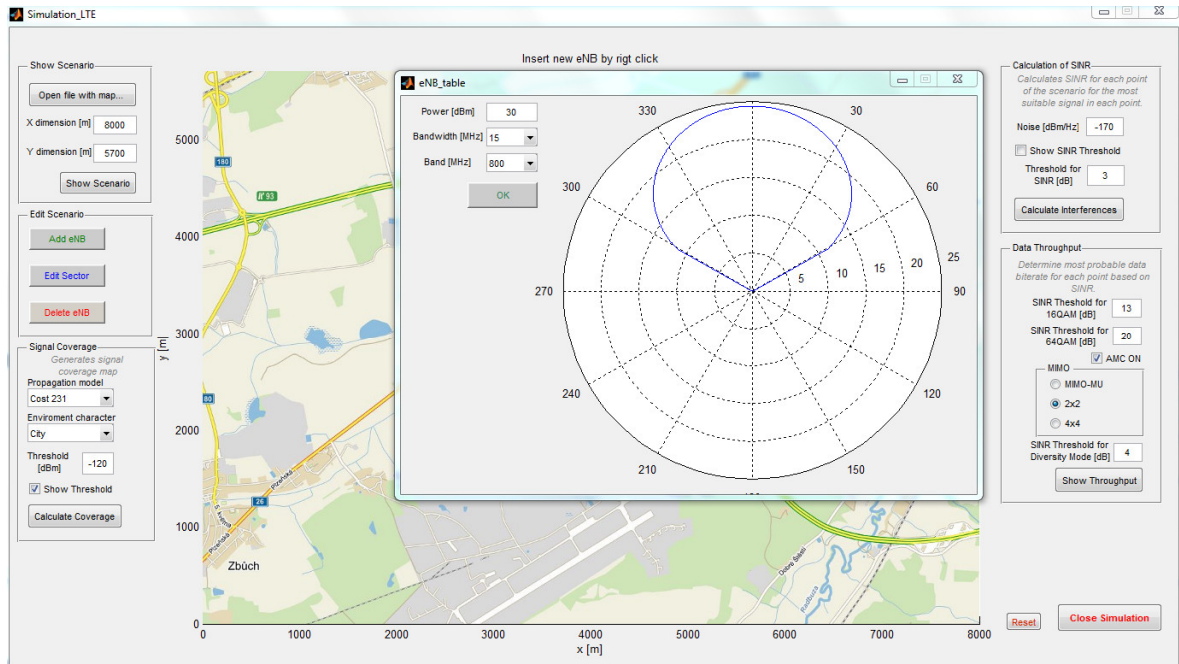


Figure 6.1 Process of creating a scenario

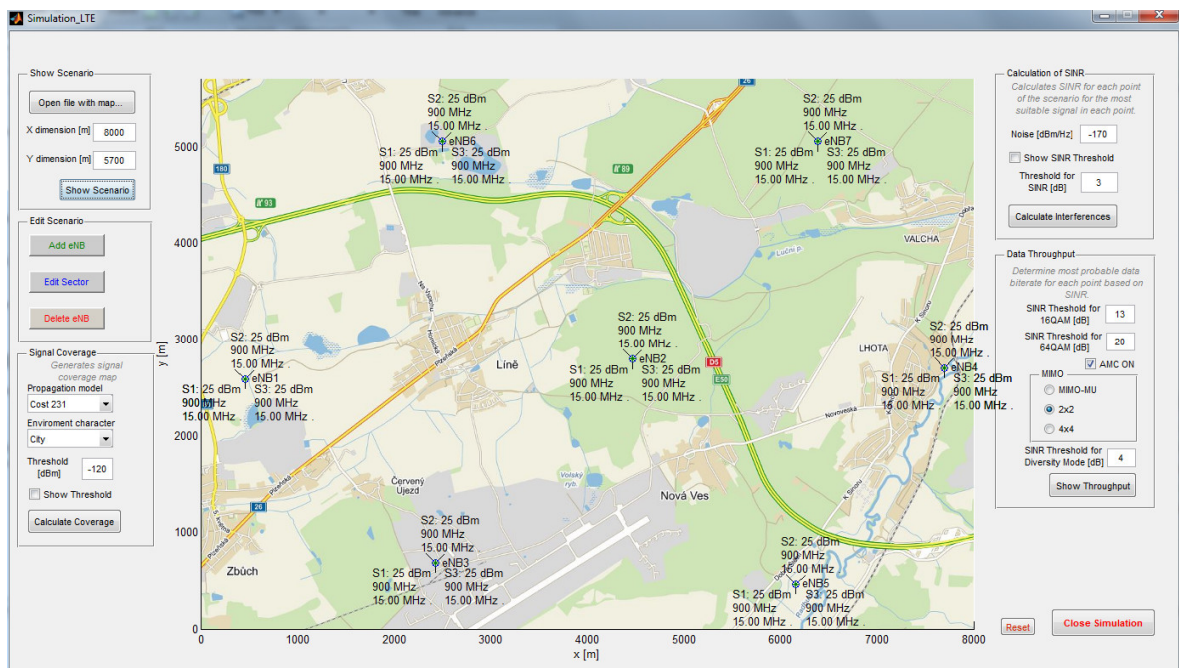


Figure 6.2 Simulation program with a created scenario

Based on the calculated SINR, the throughput of the network is determined using an algorithm approaching the AMC technology. For areas with SINR over the 64QAM threshold the 6-bit modulation is used. In areas with SINR between the 64QAM Threshold and the 16QAM Threshold the 4-bit modulation is used, for areas with SINR under the 16QAM Threshold 2-bit QPSK modulation is used. Also in areas with SINR under the Diversity Mode Threshold, the MIMO technology does not improve the throughput.

## 6.2 Simulation Results

The area of 45.6 square kilometers was covered by signal from seven eNBs. The transmitted signal power was adjusted to cover the whole area with sufficient signal without unnecessary over lapses (Figure 6.3). The full frequency reuse scheme is used in this first scenario so the same 15MHz frequency band is assigned to all the sectors. We can see in the Figure 6.4 that the SINR drops close to 0 around all the cell edges. As a consequence of that, the data rate decreases towards the cell edges (Figure 6.5). On 26% of the area the SINR is lower than 4 dB which, according to introduced thresholds, results in use of QPSK modulation and activation of diversity mode of MIMO to maintain acceptable error rates. Favorable SINR conditions (SINR > 20 dB for this particular simulation) where the transmission can reach maximum data rate are only occupying 20% of the scenario area.

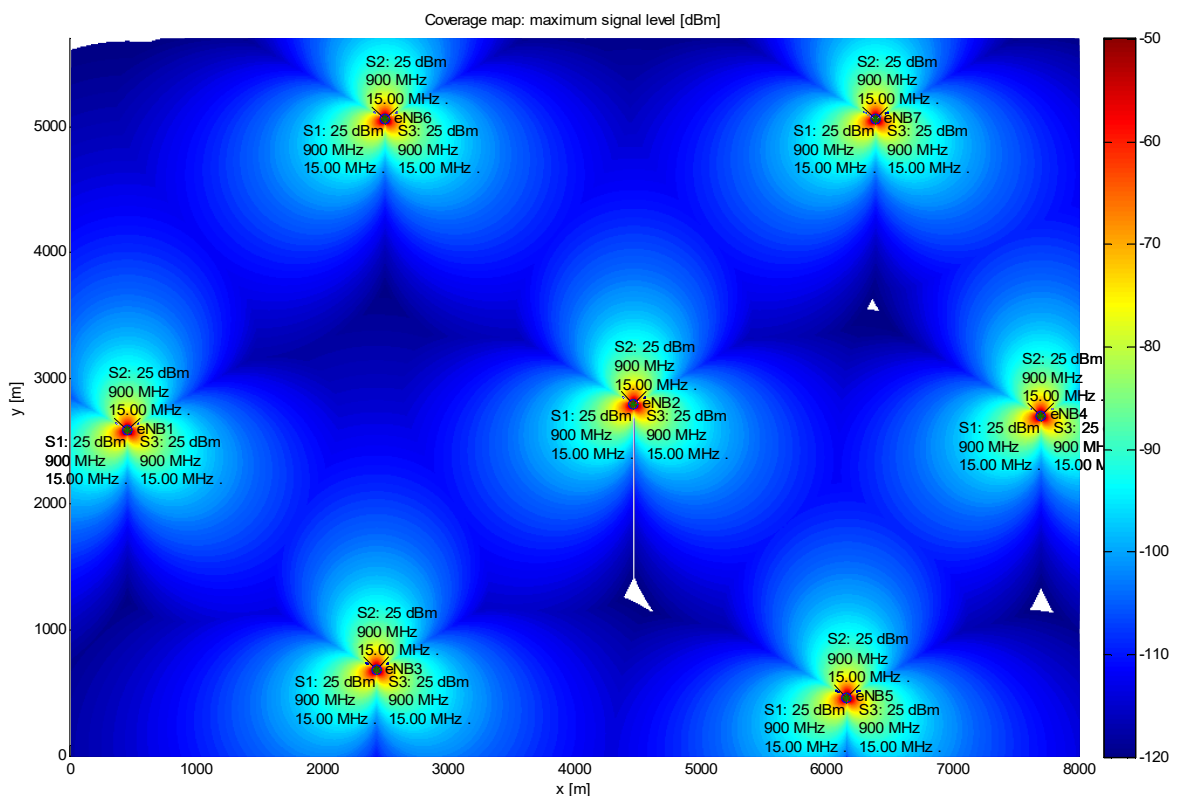


Figure 6.3 Coverage map for the first scenario: 99.8% of the area is covered with signal stronger than -120 dBm

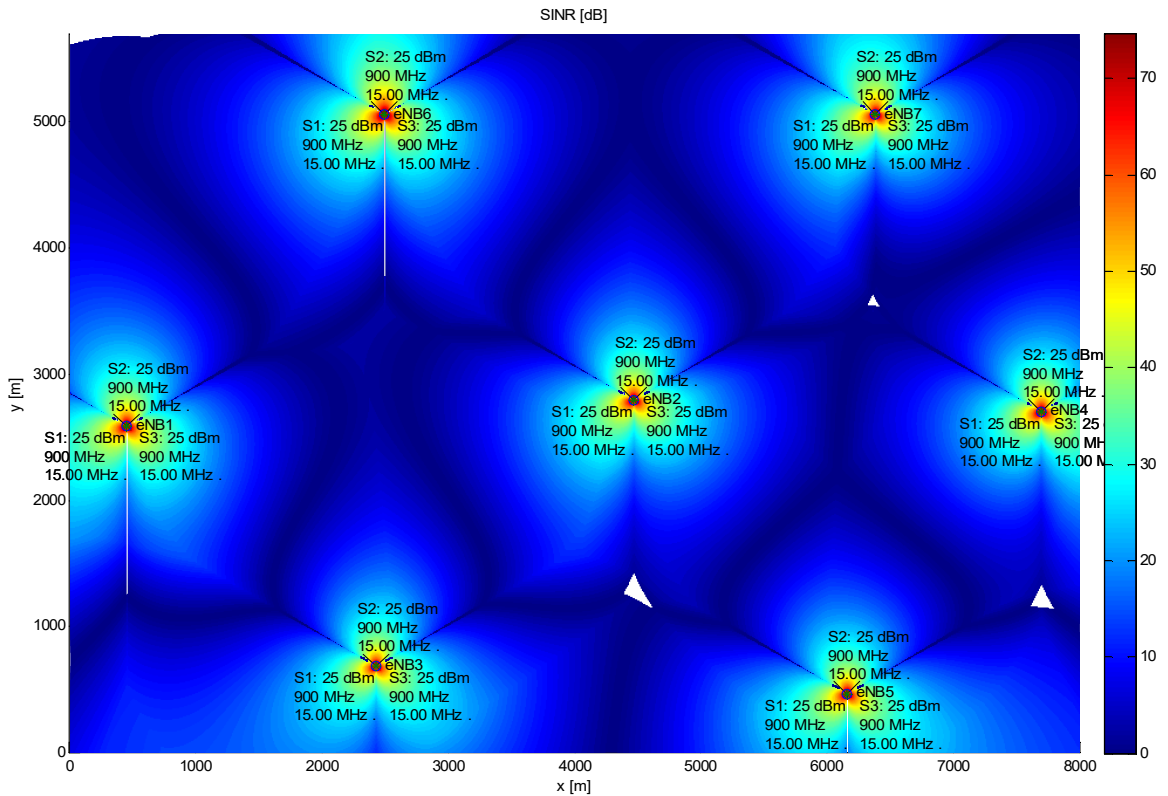


Figure 6.4 SINR map for the first scenario: SINR drops significantly around the cell edges

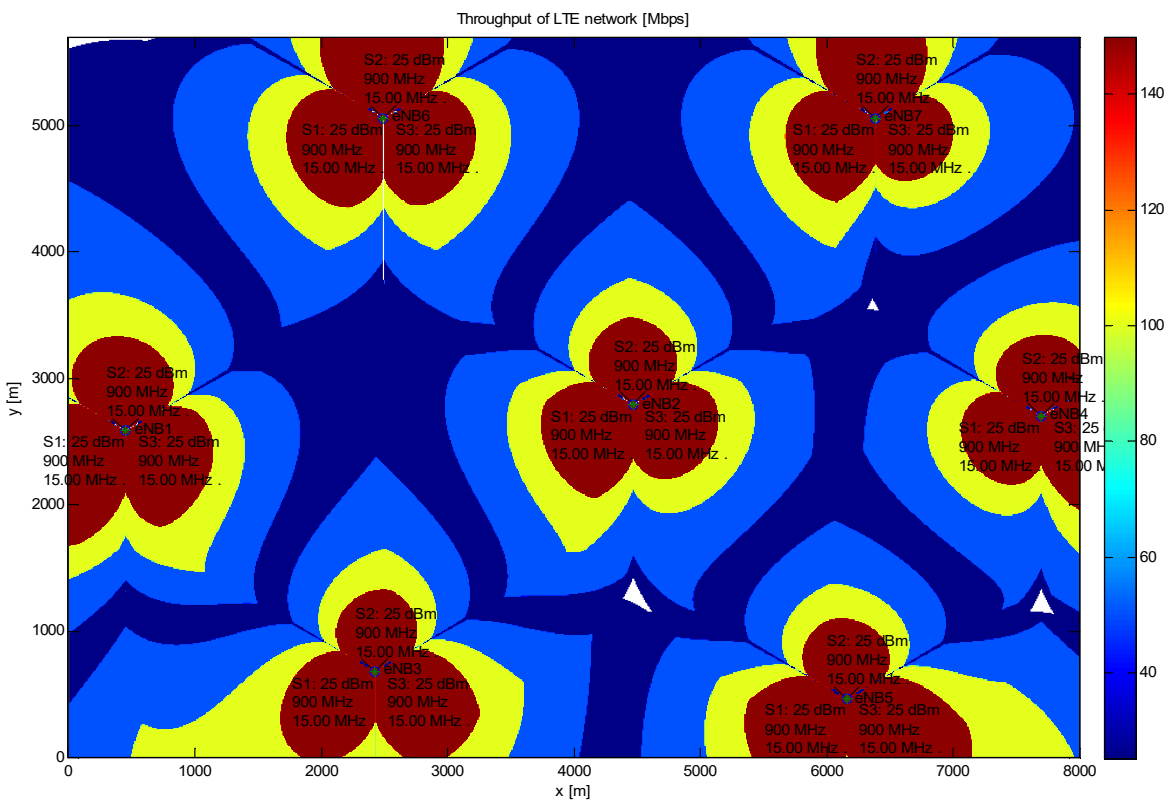


Figure 6.5 Data rate map for the first scenario: 20% of the area allows up to 151.2 Mbps, 26% of surface around cell borders only 25.2 Mbps due to low SINR

The same area was covered again by eNBs using hard frequency reuse. Cells are covered by antennas using 5 MHz bandwidth. This frequency band is different for each sector of an eNB, following the frequency reuse scheme. In this case, SINR improved significantly in the whole area. Consequently, the area where the maximum speed connection can be delivered is 60% for this scenario (Figure 6.7). However, the maximum data rate is lower in the whole area due to the bandwidth being reduced to 5 MHz. On the other hand, the area with critical SINR, where MIMO would switch to diversity mode, is minimal. This means that the connection will be more stable and less vulnerable to interferences of other sources, (which are not included in the simulation), or to fading.

The third scenario is a combination of previous approaches. Left part of the area is mainly covered by the eNB6. Together with smaller cells, covering the central part, they follow hard frequency reuse from the second scenario. The right part of the map, where urban area starts, is served by eNB4. This one has assigned the whole 15MHz band to each cell. This scenario is resource-saving. The less inhabited part is given lower capacity but stable connection using bigger cells and less frequency resources. On the other hand, the urban area is covered with more capacity and higher maximum data rate for potential subscriber.

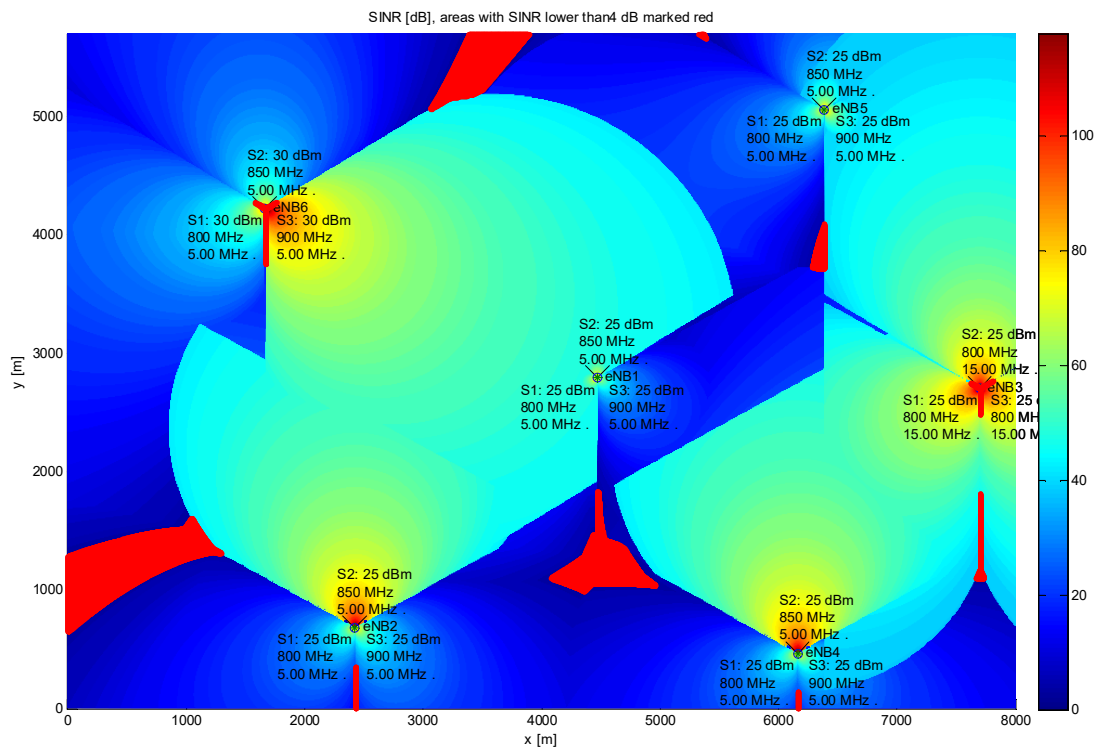


Figure 6.6 SINR map for the third scenario – areas with critical SINR marked red

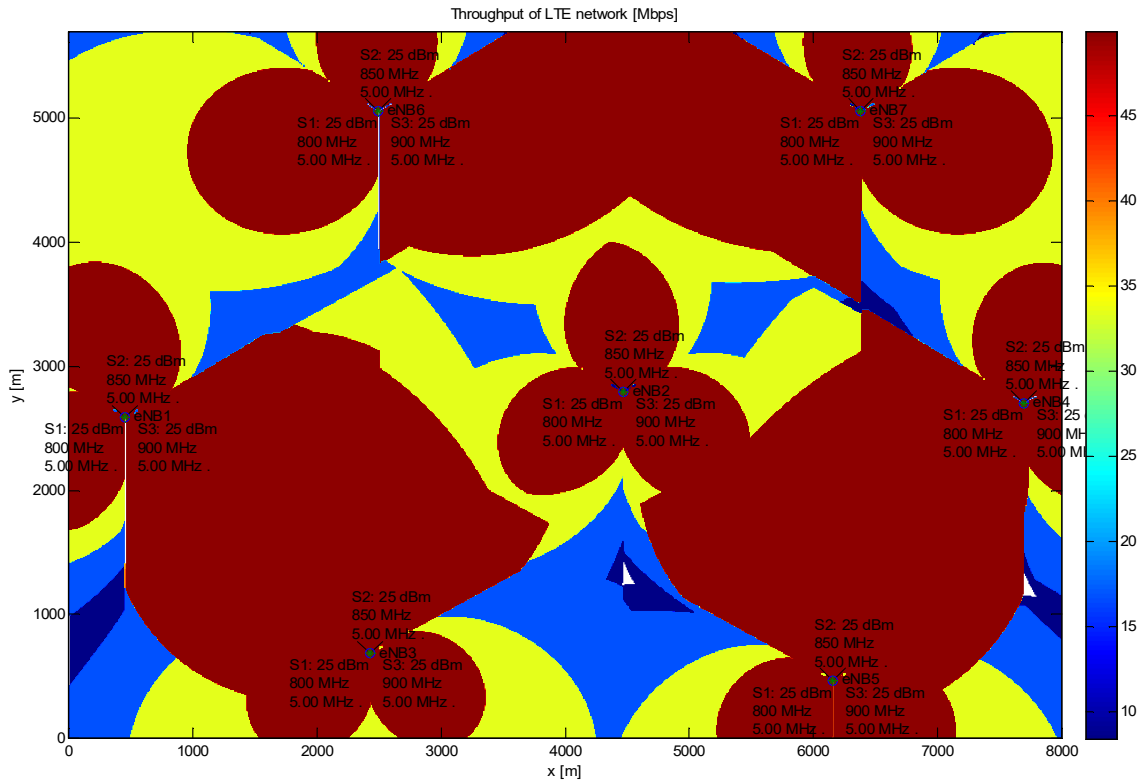


Figure 6.7 Data rate map for the second scenario: hard frequency reuse allows maximum data rate (50.4 Mbps) on 60% of the area

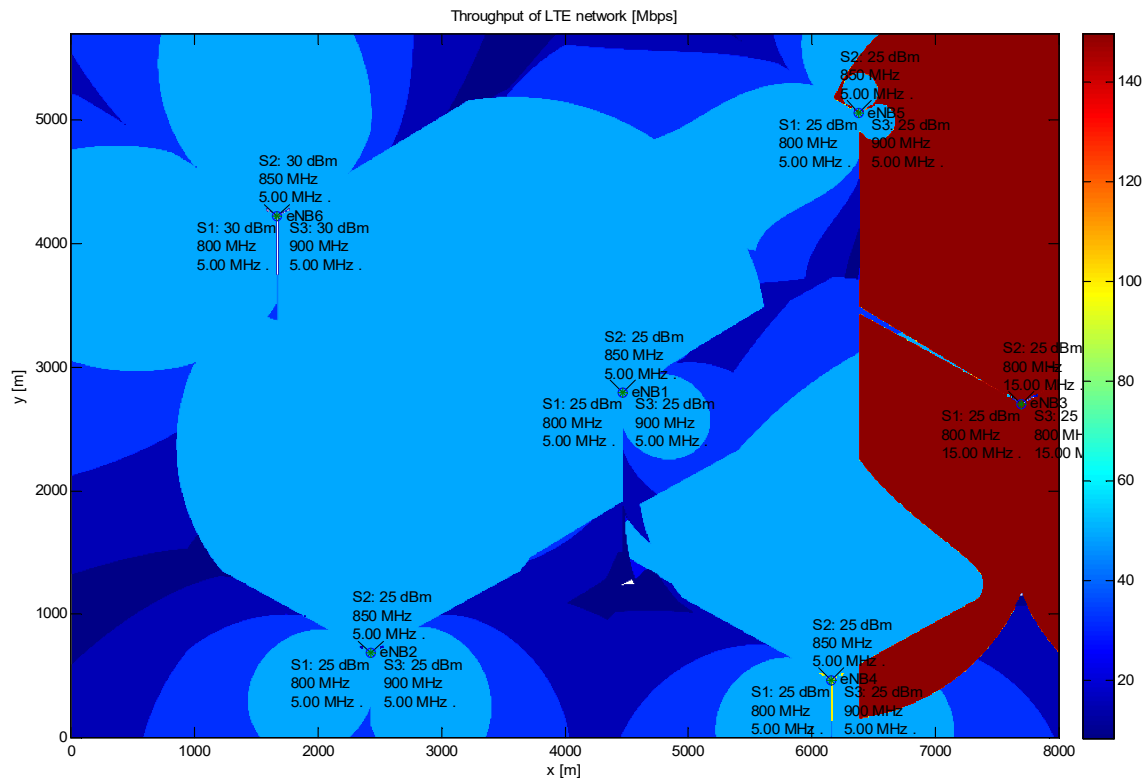


Figure 6.8 Data rate map for the third scenario: 151.2 Mbps on 15.8% and 50.4 Mbps on 57% of the area

Critical areas with low SINR (Figure 6.6), although minimal, are still present in the third scenario. This would be improved by deployment of power control and scheduling. Data rates of the inside areas of the cells could be improved by implementation of soft frequency reuse.

### 6.3 Technical Realization of the Simulation Program

The simulation was created in MATLAB based on simulation of coverage for GSM networks [29]. The program consists of 15 user functions and one secondary user interface (Attachment B). The functions are called from the main program “Simulation\_LTE.m”. The main program is interconnected with the user interface file “Simulation\_LTE.fig”. Code of all the functions together with their overview is contained in the attachments of this thesis.

All the important variables (Attachment C) are stored in the structure “s” as a part of handles of the GUI figure. Coverage maps are stored as two or three dimensional matrixes, where each element presents value for one square meter. MATLAB build-in functions for matrix operations are used preferably for their good performance. The disadvantage of this approach is that a single variable can occupy a lot of memory. Data is mainly stored as 16-bit integer. However, signal coverage maps are stored as the 32-bit single data type to avoid discontinuity in the presented coverage maps. In the created scenario with dimensions of 8000 per 5700 meters and 21 antennas, the program generates coverage maps of 3.83 GB. MATLAB can run into an error for lack of RAM memory while simulating extensive scenarios. In some cases, loops running over these matrixes had to be created. This results in time consuming operations. The most critical task is the calculation of signal coverage, which took approximately 3 minutes on the computer (2.50 GHz, 24 GB RAM) utilized to simulate the presented scenarios, while the rest of the tasks took up to 30 seconds. These intervals may vary with the particular PC’s performance and scenario.

#### 6.3.1 Calculation of coverage

Coverage is calculated based on distance from the transmitter and assigned frequency using the COST-231 or the Okumura-Hata model [29]. The effective height of transmitting antennas is fixed on 30 meters and receiving height on 2 meters. Choice of environment in



the user interface has effect on the propagation via correction parameters. Both models are fully valid from 1 km distance. The Okumura-Hata model is only designed for frequency range 150 MHz – 1500 MHz. Therefore, for higher frequencies it is necessary to use the COST-231 model, which is valid for frequencies between 1500 MHz and 2000 MHz. There are more sophisticated models for LTE planning, but they require more input variables, which are not available in this simulation. These models can be found in [11].

The level of the signal is calculated for each of the used frequency bands and stored in variable “signalmap” as a three-dimensional matrix. Maximum for each point of the map is found and stored in two-dimensional matrix “maxmap”. This matrix is presented graphically as the coverage map in the first step of the simulation. After the calculation of coverage, the percentage of covered area is printed to MATLAB command window.

### 6.3.2 Antenna Characteristics

LTE networks use antenna arrays. Their patterns can be adjusted with phase shift of signals for each element. The pattern of antenna arrays used in this simulation was modeled using parameterized Sinc function (6.1). Parameter  $a$  is adjusting the beam width and  $b$  the directivity.

$$\text{Mag} = \text{sinc}(a \theta \quad a \theta)^b \quad [\text{dB}] \quad (6.1)$$

The pattern of four-element antenna [30] is compared with adjusted Sinc function in the Figure 6.9. It is visible, that they are practically identical, however Sinc function creates more side lobes to all the directions. For the simulation, side lobes are removed and the beam width is adjusted to cover 120° sector.

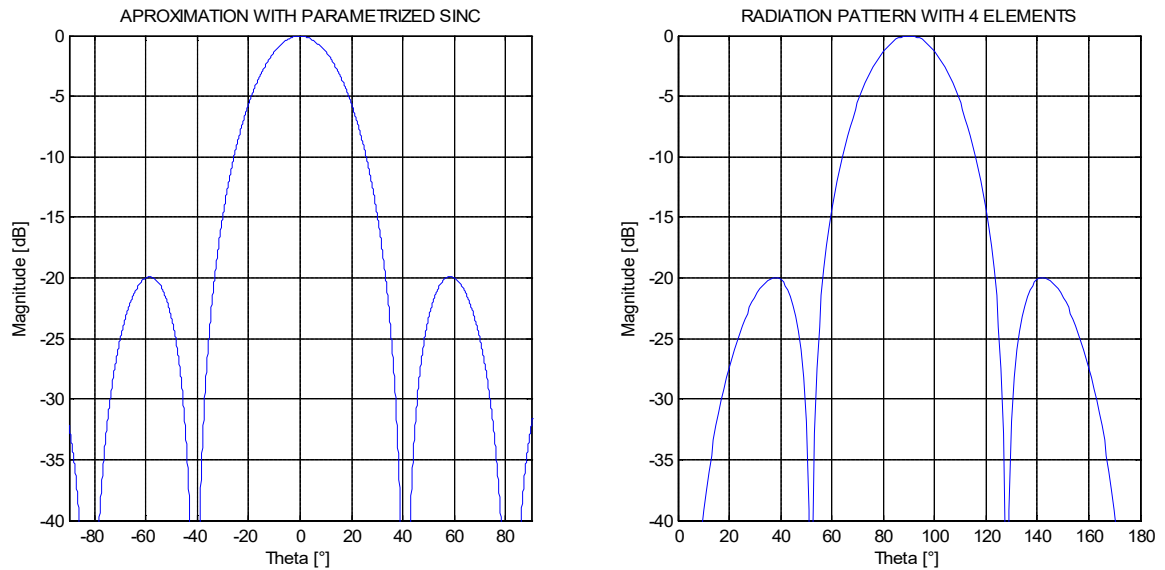


Figure 6.9 Pattern of antenna array (right) was approximated with parameterized sinc function (left)

### 6.3.3 Calculation of SINR

The SINR is calculated as the ratio of the strongest signal to the second strongest signal with the same frequency. If there is no interfering signal with the same frequency, the interfering signal is the noise. The noise level is calculated with formula (6.2) based on introduced noise value and bandwidth of the antenna. This SINR map is calculated for each frequency. In the end, the maximum value for each point is found and stored as a two-dimensional matrix in the variable “CI\_dB”.

$$P = \text{Noise} + 10 \log(B) \quad [\text{dBm/Hz, Hz, dBm}] \quad (6.2)$$

This way, the simulation is trying to find the best signal that would be available to a potential UE in each point of the simulated area.

### 6.3.4 Implementation of AMC and MIMO

Data rate is calculated based on previously calculated SINR. The number of available resource blocks for each sector is determined based on the bandwidth value stored in variable “posT” with other information about the antenna. Adaptive modulation is implemented and for  $\text{SINR} < \text{“16QAM Threshold”}$  the QPSK modulation schema is used, for  $\text{“16QAM Threshold”} < \text{SINR} < \text{“64QAM Threshold”}$  the 16QAM is used and for areas with  $\text{SINR} > \text{“64QAM Threshold”}$  the 64QAM modulation is used. These thresholds have



to be estimated because they are not standardized and in reality the order of modulation is decided by the UE and depends on the particular capability of the device.

MIMO technology is taken into account while calculating the throughput. User can choose from MIMO-MU mode, MIMO 2x2 or 4x4. MIMO-MU does not improve the data rate for single user but network's capacity. MIMO 2x2 increases the throughput two times and MIMO 4x4 four times for one hypothetical user. In areas with SINR level under the "Threshold for diversity mode" the data speed drops, which simulates the passage to diversity mode where MIMO helps to fight low SINR and does not directly improve data throughput.

$$75 \cdot 12 \cdot 7 \cdot 2 \cdot 6 \cdot 2 = 151200 \text{ [bit ms}^{-1}\text{]} \quad (6.3)$$

To give an example of data throughput calculation, we can assume 15MHz bandwidth. That means 75 Physical Resource Blocks (PRBs). Each of PRBs consists of 12 subcarriers. There are 7 symbols per subcarrier (assuming normal cyclic prefix). Each symbol is transmitted in a 0.5 ms slot. If 2x2 MIMO is used, then the maximum data rate in the location with excellent reception, where 64QAM carrying 6 bits per symbol can be used, is calculated as (6.3).

## Conclusion

The main goal of this thesis was to explore the technologies used for interference optimization and mitigation and simulate their effect on data throughput. On the presented simulation, it is visible how important network optimization and deployment of technologies capable of increasing spectral efficiency and therefore avoiding interferences is. In a purely optimized network, the whole potential of high data rates would be ruined by interferences in a major part of the network area. Therefore, technologies such as power control, scheduling algorithms and frequency reuse have been investigated, improved and deployed in LTE. AMC and MIMO technologies are being continuously developed and there are some new technologies in LTE such as, for example, adaptive beam forming. Although all these technologies have been brought to maximum efficiency, it is necessary to combine various types of technologies and a quality scheduling algorithm to achieve a functional and efficient network with reuse pattern close to  $N=1$  in order to deliver maximum throughput.

Network optimization is a part of the network planning process. LTE networks are very complex and their planning takes into account many factors. All the tasks of site planning (coverage planning, capacity planning, frequency planning) are interconnected and cannot be carried out separately. Professionally used Radio Network Planning tools are complex and expensive programs. They are able to visualize coverage, capacity and potential data rates in the planned network based on introduced configuration and environment characteristics. Still, it is essential to verify and adjust the results by field measurements.

The results of the created simulation successfully visualize the impact of interferences on data throughput of LTE network and importance of network optimization. A purely optimized network is not using resources effectively and a lack of optimization could lead to malfunction. The first presented scenario is using a maximum of resources but the functionality is degraded by interferences in a large area of the network. The situation is improved in the third scenario by a combination of frequency reuse techniques and by adjusting the sizes of the cells. However, this result would not be fully satisfying and it is apparent that the implementation of other technologies to the network, such as scheduling and power control, is needed.

These technologies were not implemented in the simulation, mainly because of their complexity. To implement them, statistical data would be required. This data is not publicly accessible and it is a part of knowhow of companies creating the professional software and those who are implementing these technologies in the mobile networks. It was also not possible to visualize the advantages of soft frequency reuse due to the created algorithm, which prioritizes stronger signal. To do so, the program would have to be modified to calculate data rate maps for all the frequencies and find the maximum value for each point. This improvement would make the simulation more demanding on memory and computing time. The memory requirements would be reduced by usage of 16-bit integer for signal coverage maps, but that would create unnatural discontinuity in the simulation results.

The original simulation of coverage for GSM networks [29] was significantly modified, optimized and adapted for simulations of LTE networks. The results of the simulation give graphic visualization on how the deployment of AMC and various modes of MIMO technology affect the data throughput. These technologies react on SINR level to maintain an acceptable error rate. This interconnection is well visible from the simulation outputs. Therefore, the task of this thesis can be considered as fulfilled, although the simulation could be continuously improved to approach such a complicated system as an LTE communication network undoubtedly is.

## Literature and Sources

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## Attachments

### Attachment A – User Manual for MATLAB Simulation

The simulation program starts after running the “Simulation\_LTE.m” file. The program opens with a default scenario. This scenario can be modified in size by changing dimensions and a different map can be loaded. The jpg picture with a map must be prepared in the same resolution as the size of scenario.

To introduce a different file with information about eNBs, the posT.txt must be replaced by this file before the start of the simulation.

After the scenario is prepared, coverage map can be calculated with COST-231 or Okumura-Hata model for city/suburban area/countryside. If “Show Threshold” is selected, areas with signal level under this threshold are left white in order to see more easily which areas are covered with sufficient signal.

After calculating the coverage, SINR map can be calculated. Background noise can be introduced for each scenario. If “Show SINR Threshold” is selected, the areas with lower SINR than the introduced threshold are highlighted in red to show critical areas.

In the end, data throughput can be determined. Value of “SINR Threshold for 16QAM” determines the SINR conditions until when 16-QAM modulation can be used. “SINR Threshold for 64QAM” determines the SINR conditions until when 64-QAM modulation can be used and “SINR Threshold for Diversity mode” determines the value of SINR when MIMO switches to diversity mode. AMC can be disabled by unselecting “AMC ON”. The data rate map is calculated and presented after pressing “Show Throughput” button.

All parameters must be numbers and in a reasonable range. The simulation is closed by clicking on the “Close Simulation” button. Reset button can be used when the simulation is not ended properly and an error message is repeatedly appearing after restart.

**Attachment B – List of Created Functions in MATLAB**

<b>addBTS</b> (oldposT) return <i>posT, nT</i>	adds eNB and prompts characteristic of antennas
<b>deleteBTS</b> (posT, nT) return <i>posT, nT</i>	deletes chosen eNB
<b>editBTS</b> (posT) return <i>posT</i>	edits chosen eNB
<b>load_posT</b> (soubor) return <i>posT, nT</i>	reads info about eNBs from file posT.txt
<b>pickCell</b> (posT) return <i>index</i>	Returns number of the closest transmitter to selected point
<b>plotBTS</b> (areadim, nT, posT, freqs) return <i>void</i>	plots eNB's positions and antenna's info
<b>eNB_table</b> () return <i>power sirka vyska band nf</i>	GUI for details about a transmitter
<b>MaxMap</b> (areadim, signalmap) return <i>maxmap</i>	calculates maximum from all the coverage maps
<b>cost</b> (posT, index, areadim, correction, freqs) return <i>signalmap</i>	calculates signal values using cost-231 model
<b>OkumuraHata</b> (posT, index, areadim, correction, freqs) return <i>signalmap</i>	calculates signal with Okumura-Hata model
<b>pokryti</b> (posT, nT, areadim, model, correction, freqs) return <i>signalmap</i>	generates coverage map (3D matrix)
<b>sektDist2</b> (areadim, posT, index ) return <i>mapdist</i>	returns map with distances from the eNB to calculate coverage
<b>showMap2</b> (areadim, maxmap, posT, nT, showTreshold, treshold) return <i>void</i>	shows 2D coverage map
<b>calc_interference</b> (signalmap, posT, freqs, bg_noise, treshold) return <i>Cimap map_band</i>	calculates SINR map
<b>LTE_speed</b> (Ci_dB, maxmap, treshold, map_band, MIMO, AMC, diversityMode) return <i>speed_map</i>	calculates data rate map

**Attachment C – List of Variables**

<i>'map_soubor'</i>	name of the file with the map for background of the scenario
<i>'soubor'</i>	name of the file with info about eNBs, set defaultly as posT.txt
<i>'MIMO'</i>	MIMO mode (1, 2 or 4)
<i>'maxmap'</i>	2D matrix for signal coverage map
<i>'signalmap'</i>	3D matrix with coverage maps for each frequency
<i>'CI_dB'</i>	2D matrix for SINR map
<i>'map_band'</i>	2D matrix with values of bandwidth of best signal in each point
<i>'posT'</i>	info about sNBs (position, frequency, bandwidth, antenna char)
<i>'nT'</i>	number of antennas in the scenario
<i>'model'</i>	chosen propagation model
<i>'correction'</i>	correction for chosen environment
<i>'treshold'</i>	minimum value considered sufficient for signal coverage
<i>'showTreshold'</i>	choice if the area under the threshold is left blank
<i>'areadim'</i>	dimensions of the scenario
<i>'showtresholdSINR'</i>	choice if the area under the threshold is highlighted red
<i>'diversityMode'</i>	threshold for diversity mode of MIMO
<i>'AMC'</i>	includes info about AMC, if is activated and modulation thresholds
<i>'freqs'</i>	numbers of frequency bands and adequate frequencies in MHz
<i>'noise'</i>	introduced value of background noise
<i>'tresholdSINR'</i>	minimum value considered sufficient for SINR map



**Attachment D – MATLAB Code**

```

clc,clear
%zadání vstupních hodnot

function varargout = Simulation_LTE(varargin) % SIMULATION_LTE MATLAB code for
Simulation_LTE.fig
% Edit the above text to modify the response to help Simulation_LTE
% Last Modified by GUIDE v2.5 26-Apr-2017 19:02:56

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',   gui_Singleton, ...
                  'gui_OpeningFcn', @Simulation_LTE_OpeningFcn, ...
                  'gui_OutputFcn',  @Simulation_LTE_OutputFcn, ...
                  'gui_LayoutFcn',  [], ...
                  'gui_Callback',    []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before Simulation_LTE is made visible.
function Simulation_LTE_OpeningFcn(hObject, eventdata, handles, varargin)

% Choose default command line output for Simulation_LTE
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

%% initialize structure of userdata with default values:
s=struct('map_soubor','mapa4x5km.jpg',...
        'soubor','post.txt',...
        'MIMO',2,...
        'maxmap',0,...
        'signalmap',0,...
        'CI_dB',0,...
        'map_band',0,...
        'post',0, ...
        'nT',0, ...
        'model',1,...
        'correction',1,...
        'treshold',-120,...
        'showTreshold',0, ...
        'areadim',[3000 4000], ...
        'showtresholdSINR',0, ...
        'diversityMode',4, ...
        'AMC',[1 13 20], ...
        'freqs',[1 2 3 4 5; 800 850 900 1800 2100], ...
        'noise',-170, ... values of noise floor
        'tresholdSINR',3);

set(0,'showhiddenhandles','on');
myhandles = findobj('tag','figure1');
set(myhandles,'userdata',s);

```

```

ShowScenario_Callback(hObject, eventdata, handles)

%%

% --- Outputs from this function are returned to the command line.
function varargout = Simulation_LTE_OutputFcn(hObject, eventdata, handles)

varargout{1} = handles.output;

function XX_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from
them
s.aredim(2) = str2double(get(handles.XX, 'String')); % reads the value from
GUI interface
set(myhandles , 'userdata',s);                 % saves to handles

% --- Executes during object creation, after setting all properties.
function XX_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function YY_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from them
s.aredim(1) = str2double(get(handles.YY, 'String')); % reads the value from
GUI interface
set(myhandles , 'userdata',s);                 % saves to handles

% --- Executes during object creation, after setting all properties.
function YY_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function load_map_Callback(hObject, eventdata, handles)

s.map_soubor = get(handles.load_map, 'String'); % reads the value from GUI
interface
set(myhandles , 'userdata',s);                 % saves to handles

% --- Executes during object creation, after setting all properties.
function load_map_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on selection change in model.
function model_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from
them
s.model = get(handles.model, 'Value');         % reads the value from GUI interface
set(myhandles , 'userdata',s);                 % saves to handles

```

```

% --- Executes during object creation, after setting all properties.
function model_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on selection change in Correction.
function Correction_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from
them
area = get(handles.Correction, 'Value');      % reads the value from GUI interface
switch area                                    %to determine right value
(matlab didnt allow to chnge tag after creation)
    case 1
        s.correction = 1;
        s.noise = 2.0000e-018;
    case 2
        s.correction=2;
        s.noise = 2.0000e-018;
    case 3
        s.correction=3;
        s.noise = 2.0000e-018;
end
set(myhandles , 'userdata',s);                 % saves to handles

% --- Executes during object creation, after setting all properties.
function Correction_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in ShowTreshold.
function ShowTreshold_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from
them
s.showTreshold = get(handles.ShowTreshold, 'Value'); % reads the value from GUI
interface
set(myhandles , 'userdata',s);                 % saves to handles

function Treshold16QAM_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from
them
s.AMC(2) = str2double(get(handles.Treshold16QAM, 'String')); % reads the value
from GUI interface
set(myhandles , 'userdata',s);                 % saves to handles

% --- Executes during object creation, after setting all properties.
function Treshold16QAM_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

```

```

function Treshold_64QAM_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from
them
s.AMC(3) = str2double(get(handles.Treshold_64QAM, 'String')); % reads the value
from GUI interface
set(myhandles , 'userdata',s);                 % saves to handles

% --- Executes during object creation, after setting all properties.
function Treshold_64QAM_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function Treshold_for_int_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from
them
s.tresholdSINR = str2double(get(handles.Treshold_for_int, 'String')); % reads
the value from GUI interface
set(myhandles , 'userdata',s);                 % saves to handles

% --- Executes during object creation, after setting all properties.
function Treshold_for_int_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in AMC_ON.
function AMC_ON_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from
them
s.AMC(1) = get(handles.AMC_ON, 'Value');      % reads the value from GUI interface
set(myhandles , 'userdata',s);                 % saves to handles

% --- Executes on button press in ShowInterf.
function ShowInterf_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from them
s.showtresholdSINR = get(handles.ShowInterf, 'Value'); % reads the value from
GUI interface
set(myhandles , 'userdata',s);                 % saves to handles

% --- Executes on button press in ShowScenario.
function ShowScenario_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                 % loads userdata from them

img = imread(s.map_soubor);
if (fopen(s.soubor,'r')<0); % if the file doesnt exist
    fclose('all');
else
    [s.posT,s.nT] = load_posT(s.soubor); % Loads positions and information
about the eNBs from previous simulation
end

```

```

axes(handles.axes1);
cla
title('');
plotBTS(s.areadim, s.nT,s.postT,s.freqs);           % force axes
orientation
image(img);                                       % Plot the image of map for
orientation in the area
plotBTS(s.areadim, s.nT,s.postT,s.freqs);         % Plots positions of
eNBs
set(myhandles , 'userdata',s);                   % saves to handles

% --- Executes on button press in Add_eNB.
function Add_eNB_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                   % loads userdata from them
s.maxmap=0; s.signalmap=0; s.CI_dB=0; s.map_band=0; % free memory
img = imread(s.map_soubor);
axes(handles.axes1);
title('Insert new eNB by rigt click');
addBTS(s.postT);                                 % calls function for ading anothe
eNB in the area
title('');
[s.postT,s.nT] = load_postT(s.soubor);           % reads modified list of eNBs
axes(handles.axes1);
cla
plotBTS(s.areadim, s.nT,s.postT,s.freqs);         % Plots positions of
eNBs
image(img);                                       % Plot the image of map for
orientation in the area plotBTS(s.areadim, s.nT,s.postT,s.freqs);           %
replots the scenario
plotBTS(s.areadim, s.nT,s.postT,s.freqs);         % Plots positions of
eNBs

set(myhandles , 'userdata',s);                   % saves to handles

% --- Executes on button press in Edit_eNB.
function Edit_eNB_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI
s=get(myhandles , 'userdata');                   % loads userdata from them
s.maxmap=0; s.signalmap=0; s.CI_dB=0; s.map_band=0; % free memory
if s.postT==0                                     % if scenario was not previously created
    msgbox('Nothing to edit');
else
    img = imread(s.map_soubor);
    axes(handles.axes1);
    title('Rigt click to area of a sector to edit it's parameters');
    editBTS(s.postT);                             % calls function to edit particular
eNB (freq, Pmax)
    title('');
    [s.postT,s.nT] = load_postT(s.soubor);         % reads modified list of eNBs
    axes(handles.axes1);
    cla
    plotBTS(s.areadim, s.nT,s.postT,s.freqs);         % Plots positions
of eNBs
    image(img);                                       % Plot the image of map for
orientation in the area
    plotBTS(s.areadim, s.nT,s.postT,s.freqs);         % replots the scenario
end
set(myhandles , 'userdata',s);                   % saves to handles

% --- Executes on button press in Calc_coverage.
function Calc_coverage_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1');           % loads handles of GUI

```

```

s=get(myhandles , 'userdata'); % loads userdata from them
if s.postT==0 % if scenario was not previously created
    msgbox('Create scenario first');
else
    s.maxmap=0; s.signalmap=0; s.CI_dB=0; s.map_band=0; % free memory
%profile on
    [s.postT,s.nT] = load_posT(s.soubor); % reads list of eNBs
    s.signalmap=pokryti(s.postT, s.nT, s.areadim, s.model, s.correction, s.freqs);
% calculates the coverage map and saves into signalmap.txt

    h = msgbox('Generating figure, please wait');
    delete(findobj(h, 'string', 'OK'));
    delete(findobj(h, 'style', 'frame'));

    s.maxmap=MaxMap(s.areadim,s.signalmap);
    figure(12);
    cla
    plotBTS(s.areadim, s.nT,s.postT,s.freqs); % force axes
orientation
    img = imread(s.map_soubor);
%image(img); % Plot the image of map for
orientation in the area
    showMap2(s.areadim, s.maxmap, s.postT, s.nT, s.showTreshold, s.treshold) %
shows coverage map over the scenario
    plotBTS(s.areadim, s.nT,s.postT,s.freqs);
    title('Coverage map: maximum signal level [dBm]');
%coverage percentage
    covered=numel(find(s.maxmap>s.treshold)); % number of points covered with
signal over treshold
    surface= s.areadim(1)* s.areadim(2);
    coverage=(covered/surface)*100
    close(h)
end
%profile viewer
%s
    set(myhandles , 'userdata',s); % saves to handles

% --- Executes on button press in Delete_sector.
function Delete_sector_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1'); % loads handles of GUI
s=get(myhandles , 'userdata'); % loads userdata from them
s.maxmap=0; s.signalmap=0; s.CI_dB=0; s.map_band=0; % free memory
if s.postT==0 % if scenario was not previously created
    msgbox('Noting to delete');
else
    axes(handles.axes1);
    title('Rigt click to area of an eNB you want to eliminate');
    img = imread(s.map_soubor);
    deleteBTS(s.postT,s.nT); % calls functin for deleting eNB
    [s.postT,s.nT] = load_posT(s.soubor); % reads modified list of eNBs
    axes(handles.axes1);
    cla;
    title('');
    plotBTS(s.areadim, s.nT,s.postT,s.freqs); % Plots positions
of eNBs
    image(img); % Plot the image of map for
orientation in the area
    plotBTS(s.areadim, s.nT,s.postT,s.freqs);
end
    set(myhandles , 'userdata',s); % saves to handles

% --- Executes on button press in Calc_Interferences.
function Calc_Interferences_Callback(hObject, eventdata, handles)
myhandles = findobj('tag','figure1'); % loads handles of GUI

```

```

s=get(myhandles , 'userdata'); % loads userdata from them
s.CI_dB=0; s.map_band=0; % free memory

if s.signalmap==0 % if coverage was previously not calculated
    msgbox('Calculate coverage first');
else
    [s.CI_dB s.map_band] =calc_interference(s.signalmap, s.posT, s.freqs,
s.noise, s.treshold);
    h = msgbox('Generating figure, please wait');
    delete(findobj(h, 'string', 'OK'));
    delete(findobj(h, 'style', 'frame'));

    s.CI_dB(abs(s.CI_dB)==inf)=NaN;
    figure(21)
    cla
    %mesh(s.CI_dB);
    plotBTS(s.areadim, s.nT,s.posT,s.freqs); % force axes
orientation
    img = imread(s.map_soubor);
    %image(img); % Plot the image of map for
orientation in the area showMap2(s.areadim, s.CI_dB, s.posT, s.nT,
s.showtresholdSINR, s.tresholdSINR)
    showMap2(s.areadim, s.CI_dB, s.posT, s.nT, s.showtresholdSINR,
s.tresholdSINR) % shows coverage map over the scenario
    plotBTS(s.areadim, s.nT,s.posT,s.freqs);
    %view(2);

    if s.showtresholdSINR==0
        title('SINR [dB]');
    else % if chosen:
        [m,n]=find(s.CI_dB<s.tresholdSINR); % shows interferences in coverage
map
        figure(21); plot(n,m, 'r');
        title(strcat('SINR [dB], areas with SINR lower than ',
num2str(s.tresholdSINR), ' dB marked red'));
    end

    % axis equal;

    close(h)
end
set(myhandles , 'userdata',s); % saves to handles

% --- Executes on button press in radiobutton1.
function radiobutton1_Callback(hObject, eventdata, handles)
% --- If Enable == 'on', executes on mouse press in 5 pixel border.
% --- Otherwise, executes on mouse press in 5 pixel border or over radiobutton1.
function radiobutton1_ButtonDownFcn(hObject, eventdata, handles)

% --- Executes on button press in CloseSimulation.
function CloseSimulation_Callback(hObject, eventdata, handles)
clear
close all

% --- Executes when selected object is changed in uipanel1.
function uipanel1_SelectionChangeFcn(hObject, eventdata, handles)
myhandles = findobj('tag','figure1'); % loads handles of GUI
s=get(myhandles , 'userdata'); % loads userdata from
them
mimo = get(eventdata.NewValue, 'Tag'); % reads the value from GUI
interface

switch mimo %to determine right value
(matlab didnt allow to chnge tag after creation)
case 'mimoOFF'

```

```

        s.MIMO=1;
    case 'mimo2'
        s.MIMO=2;
    case 'mimo4'
        s.MIMO=4;
    end
    %whos s.MIMO
    set(myhandles , 'userdata', s); % saves to handles
    % --- Executes during object creation, after setting all properties.
    function axes1_CreateFcn(hObject, eventdata, handles)

    % --- Executes on button press in Data_Troughput.
    function Data_Troughput_Callback(hObject, eventdata, handles)
    myhandles = findobj('tag','figure1'); % loads handles of GUI
    s=get(myhandles , 'userdata'); % loads userdata from
    them
    if s.CI_dB==0 % if coverage was previously not calculated
        msgbox('Calculate interference first');
    else
        %maxmap=MaxMap(areadim,signalmap_lin);
        h = msgbox('Generating figure, please wait');
        delete(findobj(h, 'string','OK'));
        delete(findobj(h, 'style','frame'));
        lteSpeed=LTE_speed(s.CI_dB, s.maxmap, s.treshhold, s.map_band, s.MIMO,
        s.AMC,s.diversityMode);

        figure(23)
        %plotBTS(s.areadim, s.nT,s.posT,s.freqs); % force axes
    orientation
        img = imread(s.map_soubor);
        cla
        plotBTS(s.areadim, s.nT,s.posT,s.freqs); % force axes
    orientation

        %image(img); % Plot the image of map for
    orientation in the area
        showMap2(s.areadim, lteSpeed, s.posT, s.nT, 0, 0)
        %mesh(lteSpeed);
        plotBTS(s.areadim, s.nT,s.posT,s.freqs);
        %view(2);
        %axis equal;
        title('Throughput of LTE network [Mbps]');
        % colorbar
        close(h)
    end
    set(myhandles , 'userdata', s); % saves to handles

    function Treshhold_Callback(hObject, eventdata, handles)
    myhandles = findobj('tag','figure1'); % loads handles of GUI
    s=get(myhandles , 'userdata'); % loads userdata from
    them
    s.treshhold = str2double(get(handles.Treshhold, 'String')); % reads the value
    from GUI interface
    set(myhandles , 'userdata', s); % saves to handles

    % --- Executes during object creation, after setting all properties.
    function Treshhold_CreateFcn(hObject, eventdata, handles)

    if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUiControlBackgroundColor'))
        set(hObject,'BackgroundColor','white');
    end

    % --- Executes on button press in OpenMap.
    function OpenMap_Callback(hObject, eventdata, handles)
    myhandles = findobj('tag','figure1'); % loads handles of GUI

```



```

s=get(myhandles , 'userdata'); % loads userdata from
them

[s.map_soubor, PathName] = uigetfile('*.jpg', 'Select the MATLAB code file');

set(myhandles , 'userdata', s); % saves to handles

function edit8_Callback(hObject, eventdata, handles)
myhandles = findobj('tag', 'figure1'); % loads handles of GUI
s=get(myhandles , 'userdata'); % loads userdata from
them
s.areadim(2) = str2double(get(handles.XX, 'String')); % reads the value from
GUI interface
set(myhandles , 'userdata', s); % saves to handles

% --- Executes during object creation, after setting all properties.
function edit8_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject, 'BackgroundColor'),
get(0, 'defaultUicontrolBackgroundColor'))
set(hObject, 'BackgroundColor', 'white');
end

function DiversityMode_Callback(hObject, eventdata, handles) % treshold for
diversity MIMO mode
myhandles = findobj('tag', 'figure1'); % loads handles of GUI
s=get(myhandles , 'userdata'); % loads userdata from
them
s.diversityMode = str2double(get(handles.DiversityMode, 'String')); % reads the
value from GUI interface
set(myhandles , 'userdata', s); % saves to handles

% --- Executes during object creation, after setting all properties.
function DiversityMode_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject, 'BackgroundColor'),
get(0, 'defaultUicontrolBackgroundColor'))
set(hObject, 'BackgroundColor', 'white');
end

function BG_noise_Callback(hObject, eventdata, handles)
myhandles = findobj('tag', 'figure1'); % loads handles of GUI
s=get(myhandles , 'userdata'); % loads userdata from
them
s.bg_noise = str2double(get(handles.BG_noise, 'String')); % reads the value
from GUI interface
set(myhandles , 'userdata', s); % saves to handles

% --- Executes during object creation, after setting all properties.
function BG_noise_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject, 'BackgroundColor'),
get(0, 'defaultUicontrolBackgroundColor'))
set(hObject, 'BackgroundColor', 'white');
end

% --- Executes on button press in Reset.
function Reset_Callback(hObject, eventdata, handles) % in case program ends
incorrectly
fclose all; % and on another run gives
"badly formatted string" error
delete postT.txt
close all

```

```

clear all;
clc;

function [posT, nT] = deleteBTS(posT,nT)
% deleteBTS deletes chosen BTS (closest to where click is made)

if (nT==3) % if there is only one BTS delete all file to prevent error
of badly formatted string
    delete('posT.txt')
    nT=0;
end
if (fopen('posT.txt','r')<0); %if the file doesn't exist - do nothing
else

    index=pickCell(posT); % find the nearest BTS, meaning BTS of the desired
cell
% finds other 3 sector BTS of the eNB:
sector= posT(index, 5);
start=index-sector+1; % first sector of choosen eNB

before=posT(1:start-1,:); % posT before deleted eNB
after=posT(start+3:nT,:); % posT after deleted eNB
posT=[before; after];
nT=size(posT,1);
dlmwrite('posT.txt',posT,'\t'); % save to file
fclose('all');
end
end

function [posT,nT] = addBTS(oldposT) % addBTS place new BTS to simulation

%% adding BTS
[A,B]=getpts(); % generate new position of the BS from
clicking on previous graph
X=A(1); Y=B(1); % takes position only of the first click

%n_ant = choose_ant_number; % calls selection of number of antennas (3
or 6)
n_ant=3;
for ii=1:n_ant % always places 3 sektors
    global power sirka vyska dir Dir band nf

    Dir=ii; %goes to gui for antenna settings to rotate the dirrection is the
antenna pointing
    shift=2;
    if Dir>3 % for case of 6 antenas (soft reuse)
        Dir=Dir-3; % dirrection of antenna repeats
        shift=4; %shift antenna position more
    end
    f=eNB_table; % calling gui for introducing parameters of the transmitter
    uiwait(f) % waits for the window to be closed
    %-----
    switch Dir % shifts antennas one pixel (resp 2ú so the dont overlaps
        case 1
            Yant = Y-shift; Xant = X-shift;
        case 2
            Yant = Y+shift; Xant = X;
        case 3
            Yant = Y-shift; Xant = X+shift;
    end
    %-----
    newposT=[Yant, Xant, nf, power, Dir, sirka, vyska, band]; % ector of
info about at to be saved to the posT.txt
    if (oldposT==0) % if thereareno previous data

```

```

        posT=newposT;                % only take the the new data
    else
        posT=[oldposT;newposT];    % connect loaded and imputted position
matrixes
    end
    nT=size(posT);
    oldposT=posT;
end
%saving data
    dlmwrite('posT.txt',posT,'\t'); % save to file
    fclose('all');
end

function posT = editBTS(posT)
% editBTS edit values of chosen BTS (closest to where click is introduced)

if (fopen('posT.txt','r')<0); %if the file doesn't exist - do nothing
else
    index=pickCell(posT); % find the nearest BTS, meaning BTS of the desired
cell
    global power sirka vyska Dir band nf
    sector=posT(index,5); % reads sector of edited antenna
    power=posT(index,4); % reads sector of edited antenna
    nf=posT(index,3); % reads sector of edited antenna
    band=posT(index,8); % reads sector of edited antenna
    Dir=sector; % to show the edited antenna characteristic correctly oriented
%-----GUI-----
    f=eNB_table; % calls gui to change antenna
    uiwait(f) % waits for the gui window to be closed
%-----
    posT(index,3:8) = [nf, power, sector, sirka, vyska, band]; % place
introduced new data into the table of BTS
    % saving data
    dlmwrite('posT.txt',posT,'\t'); % save to file
    fclose('all');
end
end

function [posT,nT] = load_posT(soubor) % initializeBTS read saved
positions of BTSES
%soubor='posT.txt'
if (fopen(soubor,'r')<0); % if the file doesnt exist
    fopen(soubor,'w+');
    posT=0;
    nT=0;
else % if the fiele does exist
    posT=dlmread(soubor); % we reads saved BS
    nT=size(posT);
    nT=nT(1); % number of loaded BS
end;
fclose('all');
end

function index = pickCell(posT)
[A,B]=getpts();
Y=round(A(1));
X=round(B(1));
%pickcell=[X,Y];
x=posT(:,1); % x coordiantes of all eNBs
y=posT(:,2); % y coordiantes of all eNBs
%xl=pickcell(1); % coordinates of picked cell
%yl=pickcell(2);
dist=sqrt((x-X).^2+(y-Y).^2);
index=find(dist==min(min(dist))); % find the nearest BS,
meaning BS of the desired cell

```

```

function s = plotBTS(areadim,nT,posT,freqs) % plot positions of BTS, their name
and freq.
    % plot(XV,YV,'k--') % replot the hexagonal network
    eNB=0; % počítá vykreslené eNB a číslujeje
    axis equal
    XX=areadim(1); YY=areadim(2);
    axis([0 YY 0 XX])
    zoom on
    xlabel('x [m]')
    ylabel('y [m]')
    hold on
        if (nT>0) % process only if there is something to process

            for ii=1:nT % loop to plot every BS
                if (rem(ii,3)==1) % pro každou tři+první eNB
                    eNB=eNB+1;
                    if (0<posT(ii,1) && posT(ii,1)<XX && 0<posT(ii,2)&&
posT(ii,2)<YY) % only if BTS is inside plotted field

                        x=posT(ii,2); % coordinates of eNB
                        y=posT(ii,1);
                        d=100; % lengt of the lines of cross
                        plot([x-d x x x+d],[y+d y y-d y+d],'k') % plots cross
defining sectors
                        plot(x,y,'O',x,y,'*') % plots the eNB

                            name = strcat(' eNB ',num2str(eNB));
% prepare strings with information about eNB and sectors
                            sect1 = sprintf('S1: %d dBm\n%d MHz \n%.2f MHz .',
posT(ii,4), freqs(2,posT(ii,3)),posT(ii,8));
                            sect2 = sprintf('S2: %d dBm\n%d MHz \n%.2f MHz .',
posT(ii+1,4), freqs(2,posT(ii+1,3)),posT(ii+1,8));
                            sect3 = sprintf('S3: %d dBm\n%d MHz \n%.2f MHz .',
posT(ii+2,4), freqs(2,posT(ii+2,3)),posT(ii+2,8));

                                text(posT(ii,2)+35,posT(ii,1)+4,name)
% plotting the strings
                                text(posT(ii,2)-650,posT(ii,1)-250,sect1)
                                text(posT(ii,2)-150,posT(ii,1)+300,sect2)
                                text(posT(ii,2)+100,posT(ii,1)-250,sect3)

                                    end
                                end
                            end
                        end
                    end
                end
            end
        end
end

function varargout = eNB_table(varargin)

gui_Singleton = 1;
gui_State = struct('gui_Name', mfilename, ...
'gui_Singleton', gui_Singleton, ...
'gui_OpeningFcn', @eNB_table_OpeningFcn, ...
'gui_OutputFcn', @eNB_table_OutputFcn, ...
'gui_LayoutFcn', [] , ...
'gui_Callback', []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargin

```

```

    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end

% --- Executes just before eNB_table is made visible.
function eNB_table_OpeningFcn(hObject, eventdata, handles, varargin)

handles.output = hObject;

guidata(hObject, handles);
%% initial data for char of antenna graph and default values of the query:
global power sirka vyska dir Dir uhel uhelRad band nf

power=30; %transmitted power in mW
nf=1;      % number of freq band
band=15;   % bandwidth in MHz
sirka=0.76; %nastavuje šířku paprsku
vyska=2;   %nastavuje směrovost
%dir=0;    %uhel vyzařování
dir=Dir*120-240; % dle vybraného sektoru nastavi uhel
uhel=-180:0.1:180; %osa x (uhel)
uhelRad=uhel*pi/180;

%% plotting characteristic -----
-----
dirRad=dir*pi/180; %přepočet na radiány
Char=(sinc(sirka*uhelRad-sirka*dirRad)).^vyska; %funkce pro aproximaci
charakteristiky anteny
[U]=((Char)<(0.048));
Char(U)=0; % zmenšení vedlejších laloků
fun=@(uhel) ((sinc(sirka*uhel-sirka*dirRad)).^vyska); %definice funkce pro
integraci
omnidir=abs(abs(quad(fun,-180,180)))/360; %integral z funkce/2Pí = char
omnidirekcionální anteny
ChardB=((10*log10(Char/omnidir))); %zisk antény (vstaženo na všesměrovou)
ChardB(ChardB<0)=0; %ořízne hluboké zářezy charakteristiky
polar(uhelRad,ChardB)% polární v dB
view([90 -90]) % rotating the graph to align with simulation result
%% -----
-----

% UIWAIT makes eNB_table wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = eNB_table_OutputFcn(hObject, eventdata, handles)
% varargout cell array for returning output args (see VARARGOUT);
% hObject handle to figure
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes on button press in OK_button.
function OK_button_Callback(hObject, eventdata, handles)

close eNB_table

% --- Executes on change
function Power_Callback(hObject, eventdata, handles)

```

```

global power
power=str2num(get(handles.Power,'String'));

% --- Executes during object creation, after setting all properties.
function Power_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on selection change in chooseFreq.
function chooseFreq_Callback(hObject, eventdata, handles)
    global nf; %number of band (goes to saved file post)
    nf=get(handles.chooseFreq,'Value');

function chooseFreq_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on slider movement.
function Uhel_Callback(hObject, eventdata, handles)
%% initial data for char of antenna graph:
global sirka vyska dir uhel uhelRad

dir=(get(handles.Uhel,'Value'))*240-120 % returns position of slider
%% plotting characteristic -----
    dirRad=dir*pi/180; %přepočet na radiany
    Char=(sinc(sirka*uhelRad-sirka*dirRad)).^vyska; %funkce pro aproximaci
charakteristiky anteny
    fun=@(uhel) ((sinc(sirka*uhel-sirka*dirRad)).^vyska); %definice funkce pro
integraci
    omnidir=abs(quad(fun,-180,180))/360 %integral z funkce/2Pi = char
omnidirekcionální anteny
    ChardB=((10*log10(Char/omnidir)); %zisk antény (vstaženo na všesměrovou)
    ChardB(ChardB<0)=0; %ořízne hluboké zářezy charakteristiky
    polar(uhelRad,ChardB)% polární v dB
    view([90 -90]) % rotating the graph to align with simulation result
%%

% --- Executes during object creation, after setting all properties.
function Uhel_CreateFcn(hObject, eventdata, handles)

if isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor',[.9 .9 .9]);
end

% --- Executes on slider movement.
function Vyska_Callback(hObject, eventdata, handles)
%% initial data for char of antenna graph:
global sirka vyska dir uhel uhelRad

vyska=((get(handles.Vyska,'Value'))*2)+1 %returns position of slider from 1 to 3
%% plotting characteristic -----
    dirRad=dir*pi/180; %přepočet na radiany

```

```

Char=(sinc(sirka*uhelRad-sirka*dirRad)).^vyska; %funkce pro aproximaci
charakteristiky anteny
fun=@(uhel) ((sinc(sirka*uhel-sirka*dirRad)).^vyska); %definice funkce pro
integraci
omnidir=abs(quad(fun,-180,180))/360 %integral z funkce/2Pi = char
omnidirekcionální anteny
ChardB=((10*log10(Char/omnidir))); %zisk antény (vstaženo na všesměrovou)
ChardB(ChardB<0)=0; %ořízne hluboké zářezy charakteristiky
polar(uhelRad,ChardB)% polární v dB
view([90 -90]) % rotating the graph to align with simulation result
%%
% --- Executes during object creation, after setting all properties.
function Vyska_CreateFcn(hObject, eventdata, handles)

if isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor',[.9 .9 .9]);
end

% --- Executes on slider movement.
function Sirka_Callback(hObject, eventdata, handles)
%% initial data for char of antenna graph:
global sirka vyska dir uhel uhelRad

sirka=(get(handles.Sirka,'Value'))*2 %returns position of slider
%% plotting characteristic -----
-----
    dirRad=dir*pi/180; %přepočet na radiány
    Char=(sinc(sirka*uhelRad-sirka*dirRad)).^vyska; %funkce pro aproximaci
charakteristiky anteny
    fun=@(uhel) ((sinc(sirka*uhel-sirka*dirRad)).^vyska); %definice funkce pro
integraci
    omnidir=abs(quad(fun,-180,180))/360 %integral z funkce/2Pi = char
omnidirekcionální anteny
    ChardB=((10*log10(Char/omnidir))); %zisk antény (vstaženo na všesměrovou)
    ChardB(ChardB<0)=0; %ořízne hluboké zářezy charakteristiky
    polar(uhelRad,ChardB)% polární v dB
    view([90 -90]) % rotating the graph to align with simulation result
%%

% --- Executes during object creation, after setting all properties.
function Sirka_CreateFcn(hObject, eventdata, handles)
% hObject handle to Sirka (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: slider controls usually have a light gray background.
if isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor',[.9 .9 .9]);
end

% --- Executes on selection change in Band.
function Band_Callback(hObject, eventdata, handles)
global band;
n_band=(get(handles.Band,'Value')); % we get number of selection
option=[15 1.25 2.5 5 10 15 20 ];
band=option(n_band); % picks adequate band according to selection

% --- Executes during object creation, after setting all properties.
function Band_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUiControlBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

```

```

function maxmap = MaxMap(areadim, signalmap) %calculates maximums of signal
    XX=areadim(2);
    YY=areadim(1);
    % calculating map of maximum values
    maxmap=zeros(YY,XX,'single');
    maxmap=max(signalmap,[],3); % maximum velue on each point
    maxmap(maxmap<-150)=-150; % sets limit because of
graphical representation % tu uniform colours, LTE
    maxmap(1,1)=-150; % is defined to -140
end

%% function to calculate level of signal from one transmitter
function [signalmap] = cost(posT, index, areadim, correction, freqs)
    sektor=posT(index,5);
    number_of_freq_band=posT(index,3); % reads number of frq band of this
transmitter
    fc=freqs(2, number_of_freq_band); % finds asigned frequency)
    XX=areadim(2);
    YY=areadim(1);
    xx=posT(index,2);
    yy=posT(index,1);
    %% parameters of signal spreading (Cost231 - hata model for cities)
    Pv=posT(index,4); % Power of BTS
    hb = 30;
    hm = 2;
    %% Correction for enviroment
    switch correction
        case 1 % city
            Cm = 3;
        case 2 % sub urban
            Cm = 0;
        case 3 % open areas
            Cm = 0;
    end
    %% calculate signal level for each point
    mapdist=sektDist2(areadim, posT, index);
    a = (1.1*log10(fc)-0.7)*hm - (1.56*log10(fc) - 0.8); %correction factor
    L = 46.3 +33.9*log10(fc) - 13.82*log10(hb) - a + (44.9 -
6.55*log10(hb))*log10(mapdist/1000)+Cm;
    %% směrovost
    sirka=posT(index,6); %sirka charakteristiky anteny
    vyska=posT(index,7);
    dir=sektor*120-240; % dle vybraného sektoru nastavi uhel
    dirRad=dir*pi/180; % přečte na rad
    [X,Y] = meshgrid(0:1:XX-1, 0:1:YY-1); % vytvoří mesh (hodnota=souřadnice)
    mapAngRad=(atan2(X-xx,Y-yy)); % vypočítá uhel (azimut) Theta

    mapChar=(sinc(sirka*mapAngRad-sirka*dirRad)).^vyska;
    %mapChar=(sin(mapAngRad+dirRad)); % charakteristika v závislosti na uhlu
Theta
    %mapChar(mapChar<0)=0;%1e-15; %
    %mapChar((mapChar)<(0.048))=0;
    [laloky]=(mapChar)<(0.048);
    mapChar(laloky)=10e-30;%abs(mapChar(laloky)./5); % zmenšení vedlejších
lalok?

    % figure
    % mesh(mapChar)
    % view(2)
    % axis equal
    signalmapcharLin=mapChar.*10.^((Pv-L)./10);
    signalmap=10*log10(signalmapcharLin);
end

```



```

%% function to calculate level of signal from one transmitter
function [signalmap] = OkumuraHata(posT, index, areadim, correction, freqs)
    sektor=posT(index,5);
    number_of_freq_band=posT(index,3);           % reads number of frq band of this
    transmitter
    fc=freqs(2, number_of_freq_band);           % finds assigned frequency)
    XX=areadim(2);
    YY=areadim(1);
    xx=posT(index,2);
    yy=posT(index,1);
    %% parameters of signal spreading (Cost231 - hata model for cities)
    Pv=posT(index,4);           % Power of BTS
    hb = 30;
    hm = 2;
    %% Correction for enviroment
    switch correction
        case 1 % city
            Kr = 0;
        case 2 % sub urban
            Kr = 2*(log10(fc/28))^2 + 5.4;
        case 3 % open areas
            Kr = 4.78*(log10(fc))^2 - 18.33 * log10(fc) + 40.94
    end
    %% calculate signal level for each point
    mapdist=sektDist2(areadim, posT, index);
    a = 3.2*(log10(11.75*hm))^2 - 4.97; % correction factor
    L = 69.55 + 26.16*log10(fc) - 13.82*log10(hb) - a + (44.9 -
    6.55*log10(hb))*log10(mapdist/1000)-Kr;
    %% směrovost
    sirka=posT(index,6);           %sirka charakteristiky anteny
    vyska=posT(index,7);
    dir=sektor*120-240;           % dle vybraného sektoru nastavi uhel
    dirRad=dir*pi/180;           % přepočte na rad
    [X,Y] = meshgrid(0:1:XX-1, 0:1:YY-1); % vytvoří mesh (hodnota=souřadnice)
    mapAngRad=(atan2(X-xx,Y-yy)); % vypočítá uhel (azimut) Theta

    mapChar=(sinc(sirka*mapAngRad-sirka*dirRad)).^vyska;

    [laloky]=(mapChar)<(0.048));
    mapChar(laloky)=0;%abs(mapChar(laloky)./5);           % zmenšení vedlejších lalok?

    signalmapcharLin=mapChar.*10.^((Pv-L)./10);
    signalmap=10*log10(signalmapcharLin);
end

function signalmap = pokryti(posT,nT,areadim, model, correction, freqs)
%calcualte coverage map acoarding to chosen model

    XX=areadim(2);
    YY=areadim(1);
    signalmap=zeros(YY,XX,nT,'single');%','single'); % mapy pokrytí od jednotlivých
    vysílačů

    if (nT>0)           % process only if there is something to process
        switch model           % choose model to calculate the coverage
            case 1
                h=waitbar(0,'Calculating the coverage. Please wait...'); % show teps
                of calculation
                hw=findobj(h,'Type','Patch');
                set(hw,'EdgeColor',[0 1 0],'FaceColor',[0 1 0]) % changes the color
                to green
                for ii=1:nT

```

```

        signalmap(:, :, ii)=cost(posT, ii, areadim, correction, freqs);
        waitbar(ii/nT) %updates bar
    end;
    close(h)

    case 2
        h=waitbar(0, 'Calculating the coverage. Please wait...'); % show
    steps of calculation
        hw=findobj(h, 'Type', 'Patch');
        set(hw, 'EdgeColor', [0 1 0], 'FaceColor', [0 1 0]) % changes the color
    to green
        for ii=1:nT
            signalmap(:, :, ii)=OkumuraHata(posT, ii, areadim,
    correction, freqs);
            waitbar(ii/nT) %updates bar
        end;
        close(h)
    end

    else
        signalmap=0;
    end
end

function [ mapdist ] = sektDist(areadim, posT, index )
%SEKTDIST calculates distance from BTS to calculate coverage.
% Takes in account sectorization and calculate nonzero values only in area
% of given sector
%
%% sectorization
%a=0; asi se da vymazat
%fi0=a; fi1=a+120; fi2=a+240;
xx=posT(index,1); yy=posT(index,2);
%sektor=posT(index,5);
%% distance calculation
XX=areadim(2);
YY=areadim(1);
mapdist=zeros(YY,XX); %generates matriq of adequal dim.
for ii=1:XX,
    for jj=1:YY,
        mapdist(jj,ii)=sqrt((ii-yy).^2+(jj-xx).^2);
    end
end

[y0,x0]=find(mapdist<30); % locate if distance less than 30
mapdist(y0,x0)=30; % change distance to 30 to avoid peaks - used
modelas are not valid for this distance anyway
end

function s = showMap(areadim,maxmap,posT,nT,showTreshold, treshold) %
present calculated coverage map (maxmap)
    XX=areadim(1);
    YY=areadim(2);
    axis equal
    axis([0 YY 0 XX])
    zoom on
    xlabel('x [m]')
    ylabel('y [m]')

    if (showTreshold==1) % pokud je požadováno, zbarví se oblasti s
    nedostatečným signálem
        maxmap(maxmap<treshold)=NaN;
    end
    imagescwithnan(maxmap,jet,[1 1 1]); % plots the maxmap

```

```

axis equal
axis([0 YY 0 XX]) % axes
zoom on
xlabel('x [m]')
ylabel('y [m]')
hold on
colorbar
end

%% function to calculate CIR
function [CImap map_band] = calc_interference(signalmap, posT, freqs,
bg_noise,treshold)
    %----- waitbar -----
    h=waitbar(0, strcat('Calculating the interference. Please wait...'));
% show tepts of calculation
    hw=findobj(h, 'Type', 'Patch');
    set(hw, 'EdgeColor', [0 1 0], 'FaceColor', [0 1 0]) % changes the color
to green    fmap=zeros(XX,YY,nT);
    %----- waitbar -----
    [XX YY nT]=size(signalmap); % recovery of dimesions
    nf=length(freqs); % number of frequencies used in
network
    nf_used=numel(unique(posT(:,3))); % number of used frequencies in
the scenario

    CImap3d=zeros(XX,YY,nf_used, 'int16'); % memory allocation
    map_band3d=zeros(XX,YY,nf, 'int8');
    map_band=zeros(XX,YY, 'int8');

    for ff=1:nf; % goes over all possible
frequency bands
        nVysilac=0; % counts number of transmitters
with given frequency
        vysilacu=numel(find(ff==posT(:,3))); % how many transmitters of
this frequency appear
        if vysilacu>0 % if this frequency is used in the
simulation
            fmap=zeros(XX,YY,vysilacu, 'single');
            posT_fmmap=zeros(vysilacu,8); % info about transmitters of this freq
            for ii=1:nT
                if(posT(ii,3)==ff) % frekvence ii-tého
vysílače odpovídá frekvenci hledané (ff)
                    nVysilac=nVysilac+1; % counts them
                    fmap(:, :, nVysilac)=(signalmap(:, :, ii)); % add covermap with
adequate frequency
                    posT_fmmap(nVysilac, :)= posT(ii, :); % reorganise info about
antennas to match fmap
                end
            end

            [carrier posMax]=max(fmap, [], 3); % first maximum on the
same freq
            vectB=posT_fmmap(:, 8);
            Bmap_pom=vectB(posMax); % matching map of
bandwidth
            map_band3d(:, :, ff)=Bmap_pom; % saves it on side of
bmaps for other freqs

            [m,n,o] = size(fmap); % generates indexes of found
maximum
            dim1 = mod((0:m*n-1), m)+1;
            dim2 = ceil((1:m*n)/m)';
            dim3 = posMax(:);
            position = sub2ind(size(fmap), dim1, dim2, dim3);
            position = reshape(position, m, n, 1);

```

```

        fmap(position)=-inf; % sets value on positions of
previous maximums to -infinity
        interf=max(fmap,[],3); % find second maximum

        rec_noise=bg_noise + 10*log10(Bmap_pom); % calculates noise for each
point

        interf(interf<rec_noise)=rec_noise(interf<rec_noise); % if there is no
interf. signal - noise is the interference signal
        carrier(carrier<treshold)=NaN; % if there is no
signal -> there is NaN signal

        CImap3d(:,:,ff)=carrier-interf; % calculate CIR itself for each freq

    end
    waitbar(ff/nf); %updates waitbar
end

[CImap ind]=max(CImap3d,[],3); % gets maximum SNIR for each point and position

% replicates indexes in other dimensions
[m,n,o] = size(CImap3d);
dim1 = mod((0:m*n-1)', m)+1;
dim2 = ceil((1:m*n)/m)';
dim3 = ind(:);
position = sub2ind(size(CImap3d), dim1, dim2, dim3);
position = reshape(position, m, n, 1);

    map_band=map_band3d(position); % puts adequate bandwidths on positions
of found max SNIR

    close(h)
end

function [ speed_map ] = LTE_speed(CI_dB, maxmap, treshold, map_band, MIMO, AMC,
diversityMode)
    [XX YY]=size(maxmap); % obnovení rozměrů oblasti
    speed_map=zeros(XX,YY,'single'); % alokace
    map_band=single(map_band);
    %PRBs = (15 * 5) % / 1000000; % dle http://www.radio-
electronics.com/info/cellulartelecomms/lte-long-term-evolution/lte-ofdm-ofdma-
scfdma.php
    symbols_per_carrier = 7; % pro shor cyclyc prefix a 6 pro long CP
    for ii=1:XX
        for jj=1:YY
            MIMO_mode=MIMO;
            SINR=CI_dB(ii,jj); % odstup signalu od šumu pro daný bod
            signal=maxmap(ii,jj); % uroven signalu v tomto bodě
            if (AMC(1) == 1) % pokud je aktivována adaptivní modulace závisí
počet bitů na symbol na SINR

                if ((SINR== -Inf) || (signal<treshold)) % pokud není udaj o
interferencích nebo není signal dostatečný
                    modulace = -inf; % znamená že není signál - rychlost bude NaN
                else
                    if (SINR<AMC(2))
                        modulace = 2; % QPSK
                    end
                    if (AMC(3)>SINR && SINR>AMC(2))
                        modulace = 4; % 16QAM
                    end
                    if (SINR>AMC(3))
                        modulace = 6; % 64QAM
                    end
                end
            end
        end
    end
end

```

```

        end
    else
        modulace = 2;
    end
    if (SINR<diversityMode) % under treshold for diversity mode switches
MIMO to diversity mode
        MIMO_mode = 1; % diversity mode
    end
    B=map_band(ii,jj); % recover information about f band i this point
    PRBs = (B * 5); % dle http://www.radio-
electronics.com/info/cellulartelecomms/lte-long-term-evolution/lte-ofdm-ofdma-
scfdma.php
    speed_map(ii,jj) = (modulace * PRBs * 12 * symbols_per_carrier * 2000 *
MIMO_mode)/1000000;
    % PRBs x subcarriers x symbols per subcarrier x (1/čas timeslotu) x
bit/symbol dle modulace x MIMO
    end
end
    speed_map(abs(speed_map)==inf)=NaN;
    speed_map((speed_map)==0)=NaN;
% percentage of max speed coverage:
    maxspeed=numel(find(speed_map==max(max(speed_map))));
    %maxspeed=numel(find(speed_map<30));
    surface=XX*YY;
    max_speed_coverage=(maxspeed/surface)*100
end

```

```

function [h hcb] = imagescwithnan(a,cm,nanclr) %
%from http://stackoverflow.com/questions/8481324/contrasting-color-for-nans-in-
imagesc
% IMAGEESC with NaNs assigning a specific color to NaNs

%# find minimum and maximum
amin=min(a(:))-1;
amax=max(a(:));
%# size of colormap
n = size(cm,1);
%# color step
dmap=(amax-amin)/n;

%# standard imagesc
him = imagesc(a);
%# add nan color to colormap
colormap([nanclr; cm]);
%# changing color limits
caxis([amin-dmap amax]);
%# place a colorbar
hcb = colorbar;
%# change Y limit for colorbar to avoid showing NaN color
ylim(hcb,[amin amax])
if nargout > 0
    h = him;
end

```

**Attachment E – Optimized Scenario**

2792.9	4467.4	1	25	1	0.76	2	5
2796.9	4469.4	2	25	2	0.76	2	5
2792.9	4471.4	3	25	3	0.76	2	5
684.29	2425.1	1	25	1	0.76	2	5
688.29	2427.1	2	25	2	0.76	2	5
684.29	2429.1	3	25	3	0.76	2	5
2702.3	7696.9	1	25	1	0.76	2	15
2706.3	7698.9	1	25	2	0.76	2	15
2702.3	7700.9	1	25	3	0.76	2	15
465.74	6159.3	1	25	1	0.76	2	5
469.74	6161.3	2	25	2	0.76	2	5
465.74	6163.3	3	25	3	0.76	2	5
5057.1	6385.1	1	25	1	0.76	2	5
5061.1	6387.1	2	25	2	0.76	2	5
5057.1	6389.1	3	25	3	0.76	2	5
4220.9	1665.8	1	30	1	0.76	2	5
4224.9	1667.8	2	30	2	0.76	2	5
4220.9	1669.8	3	30	3	0.76	2	5