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Muting pattern strategy for positioning in cellular networks

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Abstract

Location Based Services (LBS) calculate the position of the user for different purposes like advertising and navigation. Most importantly, these services are also used to help emergency services by calculating the position of the person that places the emergency phone call. This has introduced a number of requirements on the accuracy of the measurements of the position. Observed Time Difference of Arrival (OTDOA) is the method used to estimate the position of the user due to its high accuracy. Nevertheless, this method relies on the correct reception of so called positioning signals, and therefore the calculations can suffer from errors due to interference between the signals. To lower the probability of interference, muting patterns can be used. These methods can selectively mute certain signals to increase the signal to interference and noise ratio (SINR) of others and therefore the number of signals detected. In this thesis, a simulation environment for the comparison of the different muting patterns has been developed. The already existing muting patterns have been simulated and compared in terms of number of detected nodes and SINR values achieved. A new muting pattern has been proposed and compared to the others. The results obtained have been presented and an initial conclusion on which of the muting patterns offers the best performance has been drawn.

Acknowledgement

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Abbreviations

AECID	Adaptive Enhanced Cell Identity
A-GNSS	Assisted Global Navigation Satellite Systems
AoA	Angle of Arrival
CID	Cell ID
CoMP	Coordinated Multipoint
CS	Coordinated Scheduling
DCM	Dynamic Cell Muting
E-CID	Enhanced Cell-ID
eICIC	Enhanced Inter Cell Interference Coordination
eNB	E-UTRAN Node B or Evolved Node B
E-SMLC	Evolved Serving Mobile Location Center
FCC	Federal Communications Commission
FDM	Frequency Domain Muting
GDOP	Geometrical Dilution Precision
GMLC	Gateway Mobile Location Center
GNSS	Global Navigation Satellite Systems
ICI	Inter Cell Interference
ICIC	Inter Cell Interference Coordination
I_{PRS}	PRS configuration Index
ISI	Inter Symbol Interference
LBS	Location Base Services
LIS	Low Interference Subframe
LPP	Location Positioning Protocol
LPPa	Location Positioning Protocol Annex
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
MME	Mobile Management Entity
OFDM	Orthogonal Frequency Division Multiplexing
OTDOA	Observed Time Difference of Arrival
PCI	Primary Cell Identification
PRS	Positioning Reference Signal
QPSK	Quadrature Phase-Shift Keying
RF	Radio Frequency
RSTD	Reference Signal Time Difference
RTT	Round-Trip Time
RX	Received Timing Deviation
SINR	Signal-to-Interference-plus-Noise-Ratio
SPL	SUPL Location Platform
SUPL	Secure User Plane Location
TDM	Time Domain Muting
TOA	Time Of Arrival
UE	User Equipment
ULP	User-plane Location Protocol

1. Introduction

Location Based Services (LBS) are services that calculate the position of the user and constitute an essential part in our day to day activities. Positioning services are being used in almost every application, from advertising points of interest close to the user to navigation applications that every morning choose the best route between the user's house and workplace. Most importantly, location services are being used to help the emergency services by calculating the position of the user when an emergency phone call is placed. In this situations, positioning is no longer an extra feature, but a crucial factor and therefore it has high accuracy requirements on the measurements.

1.1 Motivation

Achieving high accuracy in positioning is a challenge and it is affected by several factors. Users' mobility, the varying load of the network and the different types of environments in which the users are can all affect the quality of position estimations. The use of positioning services for emergency phone calls has also placed requirements on the level of accuracy of the measurements. In 1996, the Federal Communications Commission (FCC) in the United States issued the E911 regulation. This regulation was meant to improve the emergency services response time by requiring the mobile operators to provide the location of the user. The initial requirements where to locate 67% of the calls with an accuracy of 100 meters and 95% with an accuracy of 300 meters [1]. These requirements shall have been achieved by the end of 2005. Now, the regulations are even harder, expecting an accuracy of less than 50 meters for 80% of all mobile phone calls by 2021 [2]. In the European Union, there are no binding regulations for the accuracy requirements of wireless emergency phone calls, even though more than 60% of all emergency phone calls are done from mobile devices [3].

Additionally, 50% of all wireless calls are connections established from indoor environments, which discards the use of traditional satellite systems, such as Global Navigation Satellite Systems (GNSS), for positioning. These systems need to have a direct line of sight between the user and a minimum of 4 satellites to be able to estimate the user's position. In many urban environments, getting a direct line of sight with that many satellites is not guaranteed, but it can be possible. In order to improve the position estimations in urban environments, the satellite receiver gets the help of the cellular network. These are called Assisted Global Navigation Satellite Systems (A-GNSS), since the network provides the receiver with information, such as which satellites are in view, which helps the receiver to search for the satellite signals. In indoor environments, there is no reception of satellite signals, which makes A-GNSS impossible to use [3]. In these cases, the user's position is calculated using only mobile radio signals, and the Observed Time Difference Of Arrival (OTDOA) method. This method calculates the positioning of the user by measuring the time difference between signals transmitted from different cells to the user [4].

OTDOA achieves a high level of accuracy but it depends on correctly receiving a number of signals from different cells or eNBs (E-UTRAN Node B or Evolved Node B), and therefore it can be affected by the different factors that can alter those signals. When signals are transmitted through a wireless channel, they can be weakened by obstacles and also by weather phenomena, such as fog, as they pass through. Additionally, signals can interact with each other resulting in a received signal that is weaker than the original one or even completely different from what was initially transmitted. These alterations that a signal can suffer while being transmitted through a wireless channel are, what is called, interferences. In order to lower the probability of suffering from interference between signals, the observed time difference of arrival method uses its own signal, called Positioning Reference Signal (PRS) [5]. These reference signals have been created so that they cannot suffer from interference from other types of signals (this will be explained in detail in section 2.3). But the positioning signals can still suffer from interference between each other since they are transmitted simultaneously from every cell. The user device (User Equipment or UE) needs to receive signals from both close and distant cells in order to get a good position estimation. There is, then, the possibility that positioning signals coming from closer cells will overpower the signals coming from distant cells, making their reception difficult.

Knowing which signals can potentially interfere with each other allows the network to selectively stop or mute the transmission of the interfering signals at certain time instances to favor the reception of other signals. This method is known as Muting Patterns and can significantly improve the interference between PRSs. A muting pattern is a periodic sequence that the cell knows and that indicates when to send the positioning signal and when not. With the use of muting patterns, some cells will be sending the positioning signal while other cells will not be transmitting it. This will lower the number of signals being sent at the same time, therefore lowering the interference between PRSs and improving the reception of the signal by the device.

1.2 Aim

There are different sequences or algorithms that can be used within the muting patterns method. The aim of this thesis is to investigate and compare those different approaches. To compare the different algorithms, a simulation environment has been built. This simulation environment includes the necessary network elements to be able to correctly simulate the behavior of PRSs as well as the reception of the positioning signals by the mobile device. The selected muting pattern approaches have been incorporated to the simulation, where the interference between PRSs has been measured. The different muting pattern approaches have then been compared in terms of interference produced.

This thesis has been developed for and with the help of Ericsson, multinational company that provides both software and infrastructure in networking and communications, with headquarters in Sweden. Ericsson has been one of the pioneer companies that developed the first positioning systems. Currently, Ericsson is continuing its research in location and positioning systems, with the goal of increasing the accuracy of these systems, primarily in indoor locations, to meet the requirements given by the FCC.

1.3 Research questions

- **How does the interference between PRSs affects the precision of the positioning measurements?**
  Positioning signals are transmitted with different frequency offsets and within different subframes, but they can still interfere with each other. The subframe offset is partially determined by the PRS configuration index (I_{PRS}). This index is chosen by the different operators, and most of them tend to choose the same index. This means that for two positioning signals to interfere with each other, they only need to have the same frequency offset, since the PRS occasions in the network are synchronized [5].

  Interference in a positioning signal can lead to decoding the wrong signal, which will in turn, affect the accuracy of the positioning measurements. A study on how the interference between PRSs worsens the positioning calculations of the user device, is performed in this thesis.

- **How should the simulation environment be created? What is the minimum number of elements that should be included in the simulation environment?**
  It was suggested that the simulation environment for this thesis should be implemented in Matlab. Why should Matlab be used? Is this the best option?
  As far as how the simulation environment should look like, there were no restraints given in the initial definition of the scope of the thesis. In order to know how many and which elements should be simulated, the positioning process needs to be studied. Which elements are directly implicated in the transmission and reception of positioning signals? Which elements can modify the positioning signal? These are the elements that have been included in the simulation environment.

- **What different approaches of the muting pattern can be proposed?**
  To lower the interference between PRSs, a muting pattern can be used. With the muting pattern technique, cells send the positioning signal following a sequence, so not all of the signals are transmitted at the same time [5]. There are different approaches or sequences that could be defined within this technique. In this thesis, a study on different muting pattern sequences is done. The sequences have been simulated in the simulation environment to study the effects that they have in terms of interference between positioning signals.

- **Which approach creates less interference between PRSs?**
  After simulating the selected muting pattern sequences, the approaches have been compared. For that, the simulation environment calculates the interference between positioning signals when they arrive at the receiver. Does any of the proposed approaches improves the interference between signals?

1.4 Delimitations

The simulation environment has been implemented as simple as possible, keeping the elements on a high level. Only the elements that affect directly the positioning process will be included in the simulation environment. Other elements that are part of the network and might indirectly affect the positioning process but not producing any major changes will not be simulated. In section 3.1 the role of the elements simulated is explained and why those elements have been chosen while others have been left out of the simulation environment. Having a simulation environment with every element that is part of a network or simulating every element in a low level detail would consume all the time assigned for this thesis and the second goal, which is studying different types of muting patterns, would not be reached.

Another delimitation for this thesis is the access to real data. Access to empirical data from deployed networks could not be granted due to the privacy policies in use. Therefore, the validity of the results obtained could not be checked against empirical data. Nevertheless, the calculations used in this thesis follow the signal processing theories and the results have also been compared with the study performed by Srinivasan et al. [6].

2. Theory

In this chapter, the key concepts needed to understand how positioning works and why muting patterns are necessary will be presented. The chapter starts with an overview in section 2.1 on how positioning works in LTE networks and what different methods can be used. Out of those methods, this thesis will be focusing on OTDOA, for being the most accurate and therefore the most widely used for positioning. How observed time difference of arrival works will be explained in section 2.2. Section 2.3 offers an in depth description of the Positioning Reference Signal (PRS), signal used for positioning in the observed time difference of arrival method. What a muting pattern is will be explained in section 2.4, as well as some related work done by other authors. Lastly, a brief description of the simulation environment that will be used is done in section 2.5.

2.1 Positioning in Long Term Evolution (LTE)

As previously explained in section 1.1, using the traditional satellite based systems to calculate the position of a device when the user is indoors is not possible. In those cases, the network calculates the location of the user through the Location Services, which is the standardized name for Location Based Services in the LTE network. The location service architecture is composed by 3 elements: the Location Service Client, the Location Service Server and the Location Service Target [3].

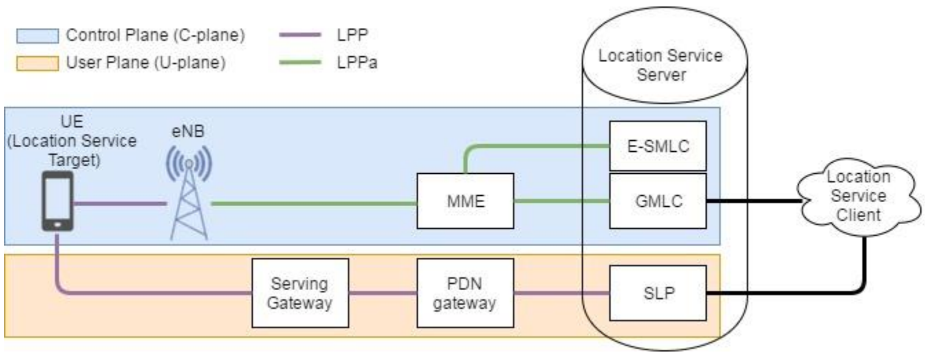


Figure 1. LTE Positioning network architecture

There are two possible architectures (Figure 1) that can be used during the positioning process. Location service messages could be exchanged over the control channels (control plane or C-plane). These channels have the advantage of being more reliable and robust [3]. The other variant, allows the messages to be exchanged as standard user data (user plane or U-plane). In this type of connection, the location service server and the mobile device can have a direct link, without having to go through other elements of the network [5].

When using the C-plane, the location service server will be the Evolved Serving Mobile Location Center (E-SMLC). There are a number of steps that are followed during the positioning process over the C-plane [5]:

1. The location service client initiates the positioning process by sending a positioning request to the Gateway Mobile Location Center (GMLC).
2. The GMLC will forward this request to the Mobile Management Entity (MME). The positioning process can also be started by the user itself through the MME.
3. The MME forwards the request to the location service server (E-SMLC).
4. The location service server processes the request and provides the user (location service target) with any information needed for the positioning calculation.

5. The MME will forward the assistant data to the user.
6. The mobile device will take the measurements needed, compute any calculations, and send the results back to the MME.
7. The MME will forward this data to the E-SMLC.
8. With the information received, the location service server will estimate the user´s position.
9. The results will be forwarded to the user or the location service by the MME.

When using the U-plane, the location service server will be the SUPL Location Platform (SPL), where SUPL stands for Secure User Plane Location. This location platform will have a direct connection with the user so the information will now be exchanged directly between them without having to be forwarded by the MME [5].

The protocol used for the exchange of the messages both in the U-plane and C-plane is the Location Positioning Protocol (LPP) and the Location Positioning Protocol Annex (LPPa) for the messages exchanged between the location service server and the cell. The location positioning protocol is a simple multiconnetion, point to point protocol with only four possible messages [3]: UE information transfer to E-SMLC, assistance data from E-SMLC to the UE, location information transfer and session management (Figure 2).

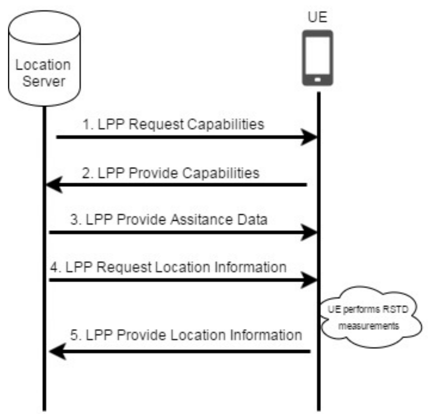


Figure 2. LPP messages

As for LPPa, the messages exchanged with this protocol contain the assistance data provided by the E-SMLC to the user and any request for information that the E-SMLC needs from the user [5].

In the user plane, the location positioning protocol will be used on top of SUPL ULP (User Plane Location Protocol) [5]. ULP provides encryption to the U-plane, and has support for E911 by prioritizing the emergency calls over non-emergency requests [3].

The positioning process in LTE can follow several methods. Some of those methods are:

- Cell ID (CID) and Enhanced Cell-ID (E-CID): this is the default positioning method when the other most accurate methods fail for some reason. Under its best conditions, cell ID has not been able to achieve more than 100 m accuracy. This method determines the position of the user based on the coverage area of the cell where the mobile phone is connected at that time. When the location service client requires positioning information about a user in the network, the location service server checks the cell-ID information in the UE. If this information is not available, the location service server will search for information on which cell the user is associated with. Once the location service server knows the cell to which the user is connected, by knowing the coverage area of such cell it is possible to know the area in which the user is located. This is not enough accuracy, since the area of a cell can have a rather large size [7].

Some additional methods can be used together with cell ID to reduce the size of the location area and improve the accuracy in the positioning. Those methods are the round-trip time (RTT), received timing deviation (RX) and Angle of Arrival (AoA) [4].

- OTDOA: this is the preferred method for indoor location due to its high accuracy. Observed time difference of arrival measures the difference between reference signals and calculates the position of the user by multilateration. More on this method can be found in section 2.2.
- RF fingerprinting: this method bases its positioning measurements in Radio Frequency (RF) measurements obtained from the user's mobile device. There are rather unique characteristics in the radio frequency measurements of the transmission of a signal. These measurements depend on the location of the user as well as the configuration of the signal. There are unique enough that they can act as a fingerprint for the user. The radio frequency measures obtained will be compared with a radio frequency measurements map. The data on the radio frequency map is generally the result of predictions or in site calculations [4].
- Adaptive Enhanced Cell Identity (AECID): this method is based in RF fingerprinting and improves it by measuring more radio properties, such as cell ID, reference signal time difference, received timing deviation and angle of arrival. The databases with reference data include OTDOA and A-GNSS measurements, together with the measured radio properties [4] [8].

2.2 Observed Time Difference of Arrival (OTDOA)

Observed Time Difference of Arrival (OTDOA) is a positioning technique based in multilateration. It measures the Time of Arrival (TOA) of a signal between the UE and several neighbor cells and also between the UE and a reference cell. The time of arrival of the measured neighbors will be subtracted from the time of arrival obtained from the reference cell. This time difference between two TOAs, each measured from one of the cells in the pair is what is called the Reference Signal Time Difference (RSTD). The position of the user can be calculated with only two RSTD measurements but for having an accurate estimation, reference signal time difference should be measured between at least three pairs of cells. These measurements result in a hyperbola. A hyperbola (Figure 3) is a conic curve defined by two focal points F_1 and F_2. Any point located in that conic curve satisfies that the difference between the distance from that point to F_1 and to F_2 is constant. Therefore, the RSTD measurement between a cell x_1 and a cell x_2 (the two focal points of the hyperbola) will result in a collection of positions in which the user could be located and still get the same reference signal time difference measurement. Therefore, in order to narrow down which of all those possible positions is the actual location of the user, at least one more RSTD measurement is needed. The new hyperbola will also define a series of possible positions for the user. The intersection point between those two hyperbolas would then be where the user is located [3].

In Figure 4, two reference signal time difference measurements have been taken to calculate the position of the user. Time of arrival was calculated for x_1, x_2 and x_3. Then $RSTD_{2,1}$ was calculated as TOA_2-TOA_1 and $RSTD_{3,1}$ as TOA_3-TOA_1, each of them resulting in a hyperbola. The point where those hyperbolas meet is where the user is located.

The equation for the hyperbolas is [5]:

$$RSTD_{i,1} = \frac{\sqrt{(x_t - x_i)^2 + (y_t - y_i)^2}}{c} - \frac{\sqrt{(x_t - x_1)^2 + (y_t - y_1)^2}}{c} + (T_i - T_1) + (n_i - n_1) \qquad (1)$$

Where the eNBs are defined as $x_i = \left[x_{i,}y_i\right]^T$, the coordinates of the user, which are unknown, are defined as $x_t = \left[x_{t,}y_t\right]^T$ and (x_1, y_1) are the coordinates of the reference cell, chosen by the user. The value c is the speed of light, $T_i - T_1$ is the offset difference in the transmission between a pair of cells which, ideally, in perfect synchronized networks should be 0. Finally, $n_i - n_1$ are measurement errors.

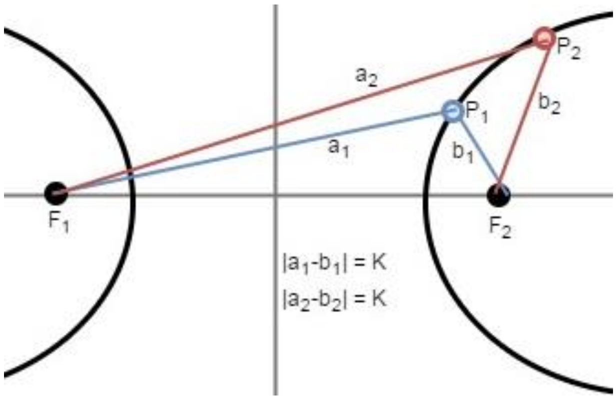


Figure 3. Features of a hyperbola.

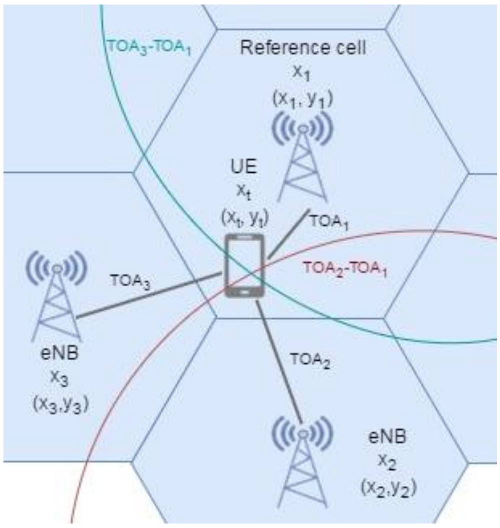
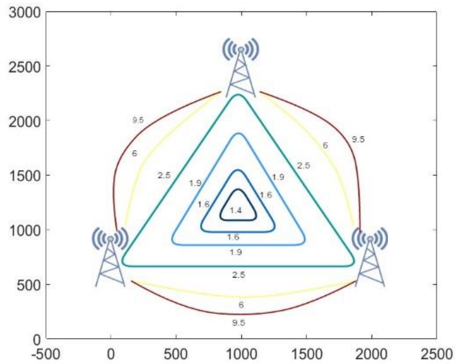


Figure 4. TDOA measurement based on hyperbolas

2.2.1 Accuracy in OTDOA

For the user's mobile device to be able to perform the OTDOA calculations, the SINR (signal-to-interference-plus-noise-ratio) of the reference cell should be higher than -6 dB and the SINR of the neighbor cells higher than -13 dB [5]. But even when these requirements are met, the precision of the OTDOA calculations can still depend on several factors [5].

- Geometry of the measurements. The number of cells used and the geometry that they form will result in additional errors in the position estimation. This error can be measured with the Geometrical Dilution Precision (GDOP) which has been calculated with the Cramér-Rao lower bound, which gives a lower bound on the variance of any estimation. In order to calculate the positioning error, the geometrical dilution precision is multiplied by the standard deviation of the RSTD measurements error.
  In a triangular geometry (Figure 5), there is only a small region in which, if the user is located there, the error in the estimation will be 1.4 or less. In a pentagonal geometry (Figure 6), the region for the minimum error is larger and the error in that region will be 0.9 or less.



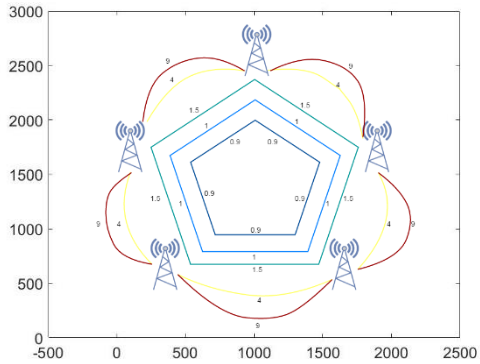


Figure 5. GDOP with 3 eNBs **Figure 6. GDOP with 5 eNBs**

- Synchronization between cells. When the network is not perfectly synchronized, there will be an offset between the signals sent from different cells. In a non-synchronized network, the term $T_i - T_1$ in ecuation (1) that ideally should be zero, cannot be ignored anymore. Since radio signals are transmitted at the speed of light, even the smallest time offset can result in errors in the positioning. The impact that this offset can have in the positioning calculations can be seen in Figure 7.

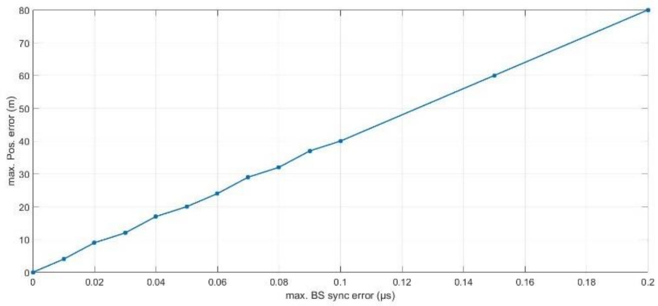


Figure 7. Impact of base station synchronization error on location accuracy

- Cell data base accuracy. As it can be seen in equation (1), one of the values needed to solve the equation are the coordinates of the cells participating in the positioning calculations. These coordinates are stored in a database, and there can be incongruences between them. They can be expressed in different units or geodetic datums, which results in an error on the position of cells and therefore an error on the position estimation of the user. The impact that an error in the coordinates of a cell can have in the positioning calculations can be seen in Figure 8.

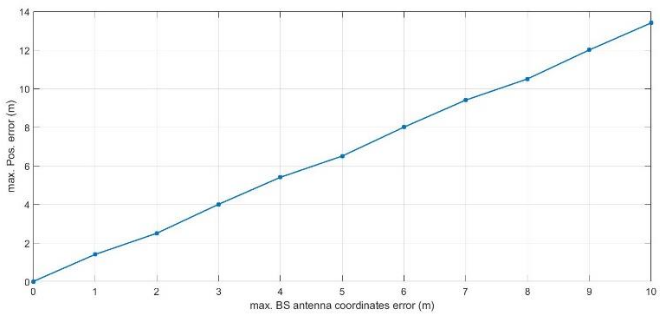


Figure 8. Impact of base station antenna coordinates error on location accuracy

- Network planning. OTDOA uses its own signal called Positioning Reference Signal. This signal has been designed for low interference; it will not have any interference with other signals in the network and it is shifted in frequency with a reuse factor of 6. Therefore, only positioning signals in the same frequency shift group can interfere with other positioning signals. This signal is explained in more detail in section 2.3. The frequency shift depends on the PCI (Primary Cell Identification) of the cell. Therefore, in order to lower the interference and improve the position calculation, the PCI planning of the network should be done so that there are no neighbor cells with the same frequency shift. But this is not the case normally in a deployed network. In order to avoid this interference, muting patterns are used. More on muting patterns will be explained in section 2.4.

- Environment. The signals transmitted through the channel can suffer from what is known as multipath effect. This means that during its transmission the signal can meet objects and obstacles that can refract, reflect or scatter the signal. This will result in the signal arriving to the receiver through different paths. Each path will cover a different distance, which means that the signal will arrive to the receiver multiple times, with multiple delays. Since the time of arrival of a signal is the needed value to calculate the position of the user, having an inaccuracy in the delay will result in an error in the positioning calculations.

2.3 Positioning Reference Signal (PRS)

The signals transmitted by a cell can be detected by a neighbor cell when the SINR is at least -6 dB. This ratio has proven to not be enough when the user's mobile device needs to detect signals that have been emitted from non-neighbor base stations. In order to improve the detection of the signals needed for the positioning calculations in OTDOA, the standard 3GPP LTE in its Release-9 defines the Positioning Reference Signal (PRS) [5].

PRS is a Quadrature Phase-Shift Keying (QPSK) sequence, modulated using Orthogonal Frequency Division Multiplexing (OFDM). This type of digital modulation encodes the data using multiple subcarriers, each one of them with a different frequency. Each individual subcarrier will be modulated using a conventional modulation technique. Multicarrier signals are robust against the channel conditions and intersymbol interference (ISI) and frequency selective fading [9].

The positioning reference signal has three layers of isolation in order to lower the interference between them [5]:

- First, each positioning signal sequence generator is initialized with a seed c_{init}. The value of this seed depends amongst other values, on the cell ID. There are 504 possible values for the cell ID, which means that there will be 504 different positioning signal sequences.
- The positioning reference signal sequence is shifted in frequency, and the value of this shift depends on the cell ID modulo 6, which means there are 6 possible frequency shifts. This frequency shift avoids the collision with cell-specific reference signals and also the overlap with the control channels.
- Lastly, positioning signals are also shifted on time. They are transmitted in a number of consecutive subframes, with a subframe offset depending on the PRS configuration index (I_{PRS}) and with a certain periodicity that also depends on the I_{PRS}. This index is chosen by the different operators. Each subframe follows the Low Interference Subframe (LIS) design, which means that the positioning signal information will not be transmitted within the data channels.

Therefore, if the network is completely synchronized, a positioning signal can only suffer from interference from another positioning signal if both have the same time shift and frequency shift. In reality, interference happens more often. Most of the operators chose the same PRS configuration index, which means that all the positioning signals have the same time shift, making the interference more probable. Even if the operators were to choose different I_{PRS}s, the I_{PRS} within a network will be the same for every cell. So even though the interference of positioning signals from different networks would be reduced, there will still be interference from positioning signals within the same network.

Also, if the positioning signals have the same frequency shift, the difference in power between them might be strong enough to not allow the receiver to detect the correct signal [5].

The positioning reference signal sequence is given by the expression [5]:

$$r_{l,n_s} = \frac{1}{\sqrt{2}}\big(1 - 2 \cdot c(2m)\big) + j\frac{1}{\sqrt{2}}\big(1 - 2 \cdot c(2m+1)\big), \quad m = 0,1,\dots,2N_{RB}^{maxDL} - 1 \tag{2}$$

Where n_s is the slot number in the radio frame. One radio frame of 10 ms has 10 subframes of 1 ms, and each subframe has 2 slots. Therefore, there are 20 slots in one radio frame, numbered from 0 to 19. The value l is the OFDM symbol number, each slot will have 7 symbols (for normal cyclic prefix) numbered from 0 to 6, or 6 symbols (in extended cyclic prefix) numbered from 0 to 5. The cyclic prefix of an OFDM signal is the repetition of the last part of the sequence at the beginning of the sequence. It is used as a guard interval that lowers or even eliminates the intersymbol interference. N_{RB}^{maxDL} is the largest downlink bandwidth configuration, in resource blocks, which can take values from 6 up to 100. N_{sc}^{RB} is the number of subcarriers. For positioning signals, there are 12 subcarriers.

The last value of the expression is c(i), which is a pseudo-random sequence defined by [10]:

$$c(n) = \big(x_1(n + N_c) + x_2(n + N_c)\big)mod2 \tag{3}$$

$$x_1(n + 31) = \big(x_1(n + 3) + x_1(n)\big)mod2 \tag{4}$$

$$x_2(n + 31) = \big(x_2(n + 3) + x_2(n + 2) + x_2(n + 1) + x_2(n)\big)mod2 \tag{5}$$

In this expressions N_c is the number of coded bits to be transmitted, which it is 1600 for normal cyclic prefix. The first sequence is initialized with $x_1(0) = 1$ and the rest of the values equal to 0. The second sequence is initialized with c_{init}.
The value of c_{init} is given by the expression [5]:

$$c_{init} = 2^{10} \cdot (7 \cdot (n_s + 1) + l + 1) \cdot \big(2 \cdot N_{ID}^{cell} + 1\big) + 2 \cdot N_{ID}^{cell} + N_{CP} \tag{6}$$

In this expression N_{CP} is 1 for normal Cyclic Prefix or 0 for extended Cyclic Prefix and N_{ID}^{cell} is the cell ID.

The Positioning Reference Signal sequence created, needs to be mapped into QPSK symbols and these symbols need to be placed into the specific resource elements allocated for the transmission of a positioning signal within each slot. This mapping is done according to the next expression [5]:

$$a_{k,l}^{(p)} = r_{l,n_s}(m') \tag{7}$$

For normal cyclic prefix:

$$k = 6\big(m + N_{RB}^{DL} - N_{RB}^{PRS}\big) + \big(6 - l + v_{shift}\big)mod6 \tag{8}$$

$$l = \begin{cases} 3,5,6, & if\ n_s mod2 = 0 \\ 1,2,3,5,6, & if\ n_s mod2 = 1\ and\ (1\ or\ 2\ PBCH\ antenna\ ports) \\ 2,3,5,6, & if\ n_s mod2 = 1\ and\ (4\ PBCH\ antenna\ ports) \end{cases} \tag{9}$$

$$m = 0,1,\dots,2 \cdot N_{RB}^{PRS} - 1 \tag{10}$$

$$m' = m + N_{RB}^{maxDL} - N_{RB}^{PRS} \tag{11}$$

For extended cyclic prefix:

$$k = 6\big(m + N_{RB}^{DL} - N_{RB}^{PRS}\big) + \big(5 - l + v_{shift}\big)mod6 \tag{12}$$

$$l = \begin{cases} 3,4,5, & if\ n_s mod2 = 0 \\ 1,2,4,5, & if\ n_s mod2 = 1\ and\ (1\ or\ 2\ PBCH\ antenna\ ports) \\ 2,4,5, & if\ n_s mod2 = 1\ and\ (4\ PBCH\ antenna\ ports) \end{cases} \quad (13)$$

$$m = 0,1, \dots ,2 \cdot N_{RB}^{PRS} - 1 \quad (14)$$

$$m' = m + N_{RB}^{maxDL} - N_{RB}^{PRS} \quad (15)$$

Where N_{PRS}^{RB} is the bandwidth of the PRS and v_{shift} is the frequency shift which is given by the expression:

$$v_{shift} = N_{ID}^{cell} mod6 \quad (16)$$

In figure 9, there are two slots represented. Each slot will be treated differently depending if the slot number is even or odd. Each slot will have 7 symbols and each symbol will have 12 carriers. For each pair of slots, two $r_{l,n_s}(m)$ values will be mapped, $r_{l,n_s}(m)$ and $r_{l,n_s}(m+1)$. Each different symbol for which information is mapped is encoding those two elements of r_{l,n_s} each with a different frequency offset given by k.

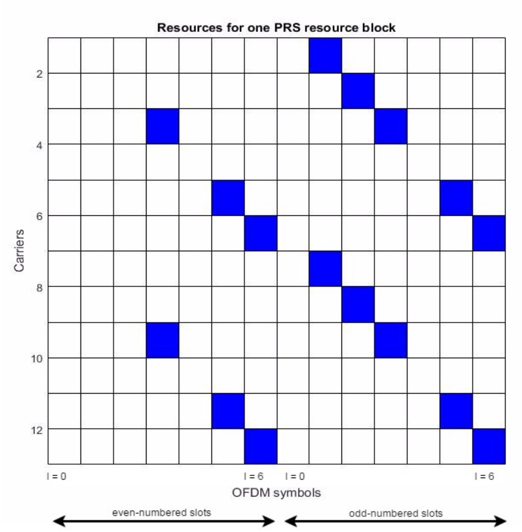


Figure 9. Mapping of positioning reference signal (normal cyclic prefix, 1 or 2 PBCH antenna ports, PCI 0)

2.4 Muting patterns

As previously explained in section 2.3, a positioning signal can only suffer from interference from other positioning signals within the same frequency shift. But interference between positioning signals is still a common phenomenon since deployed networks don't normally follow an ideal PCI planning. In an ideal PCI planning neighbor cells do not have the same cell ID and also they do not have the same frequency shift. But in a deployed network neighbor cells with the same frequency shift can still be found. This will prevent the user device from hearing a sufficient number of cells, which is needed to achieve high accuracy in the Observed Time Difference of Arrival measurements. It is then when muting patterns can be used, to further lower the interference between positioning signals. With the use of muting patterns, not all positioning signals will be sent at the same time. Some cells will stop their transmissions during certain periods of time, which will lower the interference between positioning signals and increase the number of cells the mobile device is capable of detecting.

2.4.1 Related work

The concept of muting is not uncommon in the field of signal processing and networks. The increase in data traffic as well as the introduction of concepts such as heterogeneous networks and small cells have resulted in an increased inter-cell interference (ICI). Even though LTE has several techniques to reduce the interference between cells such as MIMO (Multiple-Input Multiple-Output) and OFDM (Orthogonal Frequency Division Multiplexing), interference is still an important problem, lowering the performance of the network. Inter-Cell Interference Coordination (ICIC) was first introduced in 3GPP release 8 [11]. This method aimed to coordinate the transmissions in the network so that the interference between signals is lowered. For that, it used frequency domain muting (FDM), which mutes or stops the transmission of the resources being transmitted in a determined frequency [12].

Time domain muting (TDM) is another method for mitigating the interference between signals, and was first introduced in 3GPP release 10 [11]. It is one of the methods of Enhanced Inter-Cell Interference Coordination (eICIC). In time domain muting, a cell will stop its transmissions during certain periods of time [12]. Enhanced Inter-Cell Interference Coordination TDM can be used in combination with Coordinated Multipoint (CoMP). This technique is one of the LTE solutions to improve the performance of the network and the resource allocation. In this method, a group of cells work together to transmit or receive data to and from a user device in what is called joint processing. To reduce the interference between cells, it uses Coordinated Scheduling (CS) together with time domain muting. In coordinated scheduling the data from one mobile device will be transmitted by only one cell, as opposed to being transmitted by multiple cells. In CS with TDM, the muting pattern is chosen depending on what is called a benefit metric, in which a node sends to its neighbor a measurement of the benefit that it will get if the neighbor were to be muted.

Agrawal et al. [13] performed a comparison between a centralized CS with TDM algorithm and a decentralized version of it is made. A dynamic version of the coordinated scheduling algorithm, called Dynamic Cell Muting (DCM) is studied by Wang et al. [14], both for a heterogeneous network and a macro scenario. The same authors also test the dynamic cells muting technique for Ultra Dense Indoor scenarios [15]. Grøndalen, Mahmood and Østerbø [11] and Gadam et al. [16] studied the effects of different eICIC muting ratios in the throughput of the network. The muting ratio is the percentage of muted occasions in a muting pattern.

These papers show the usage of time domain muting for lowering the interference in the network and improving the ICI. But none of them relates the concept of muting to help positioning techniques. Oborina, Henttonen and KoivunenIn [17] proposed a muting technique to improve the accuracy of UE positioning measurements. The authors propose to mute the serving cell, the cell to which the user device is connected. This cell is normally the closer cell to the user and therefore the signals being transmitted from this cell will have higher power than signals transmitted from further nodes, overpowering them. Muting the serving cell, also called cell blanking, during certain periods of time will allow the user device to be able to detect signals being sent from distant cells which will improve the geometry of the measurements, as it was previously explained in section 2.2.

A study similar to the one that is perform in this thesis can be found in this paper done by Srinivasan et al. [6]. The authors study the effects of different muting patterns in the interference between positioning signals. The results show how many cells can be heard by the user device for each of the muting patterns studied, as it is also done in this thesis. Despite the similarities, the method used by Srinivasan et al. [6] is different from the methods followed in this thesis. The findings obtained in the previous referred paper are the result of a theoretical study where the authors have not taken into account elements of the network such as delay and pathloss depending on distance, positioning signals with different frequency shifts and the generation of the PRS itself, amongst others. In this thesis, as it will be detailed in chapter 3. Method, all these elements and others have been taken into account, as the results have been based on a simulation rather than theoretical formulas. It was expected then, that the results obtained in this thesis slightly differ from the ones obtained by Srinivasan et al. [6]. Nevertheless, the muting pattern algorithm used in that study has also been simulated in this thesis, and has served as inspiration for the development of a new muting pattern algorithm, as it will be explained in chapter 3. Method.

2.4.2 PRS muting

Time domain muting is the muting technique used in PRS muting. With this method, some positioning signals will be transmitted with constant power, while others will be muted (not transmitted) in certain time occasions. Each cell knows its muting pattern, which states when to send the signal and when to mute it. A pattern is a sequence, with a possible length of 2, 4, 8 or 16 bits. The bits in the sequence can have the value of 1 or 0, 1 means that the positioning signal is transmitted and 0 that it is muted. The sequence will be repeated over time, with a periodicity equal to the length of the pattern (denoted by T_{REP}). The sequence also has a duty cycle [6] which is a percentage of the non-muting occasions in the pattern with respect to the length T_{REP} of the pattern [5].

The muting pattern in Figure 10 has a T_{REP} of 4 and a duty cycle of 50% and corresponds to the sequence 1100.
In a network where neighbor cells have the same frequency shift (Figure 11), a muting pattern can be generated so that those cells will not be transmitting at the same time.

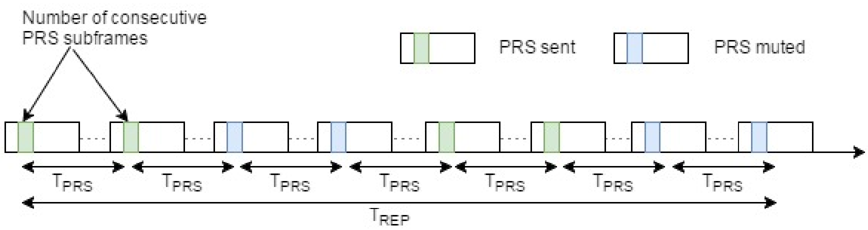


Figure 10. Example of PRS muting pattern

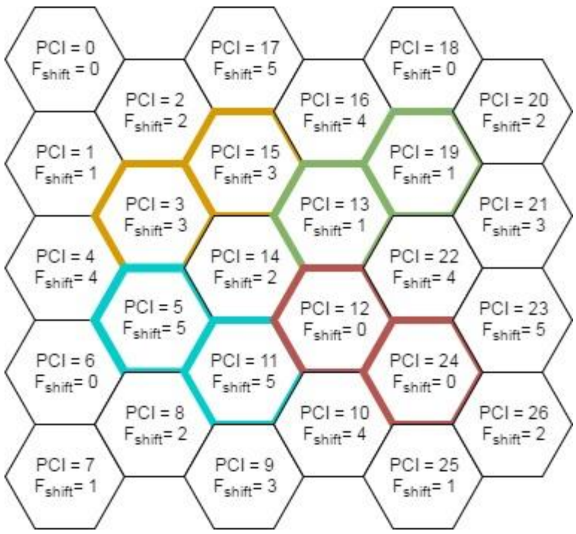


Figure 11. Example of PCI planning with interfering neighbors

In Figure 11, neighbor cells that have the same frequency shift have been underlined in the same color. The neighbor cells with PCI 5 and 11 will have the same frequency shift and therefore, will interfere each other. Same thing happens with cells 3 and 15, 12 and 24 and 13 and 19. Once a muting pattern is correctly assigned this cells will transmit in different occasions, and will not produce interference with each other. Non-neighbor cells with same frequency shift have less risk to interfere each other and are not taken into account when assigning the muting pattern.

The network in Figure 12 is using a muting pattern of 4 bits, where the positioning signal will only be sent once per sequence. The possible combinations are 1000, 0100, 0010, 0001. There are 4 possible muting pattern variations that will be given to the different nodes in the network. In Figure 12, nodes with the same background color will have the same pattern. It is possible to see now that nodes 5 and 11 have different muting patterns and will not be sending their signals at the same time. Same thing happens with the rest of the nodes that were interfering eachother. This can be seen in more detail in Figure 13. Nodes 5 and 3 can send their positioning signals at the same time since they have a different frequency shift and therefore can not interfere eachother. Nodes 11 and 15 can also send their signals at the same time but in this case (following Figure 13) they have been asigned different patterns. The interfering nodes 5 and 11 have been assign different patterns. The nodes 3 and 15 have also been assign different patterns. The pattern for nodes 5 and 3 is 1000, for node 11 is 0100 and finally for node 15 is 0010. This way, the interference between nodes will be reduced.

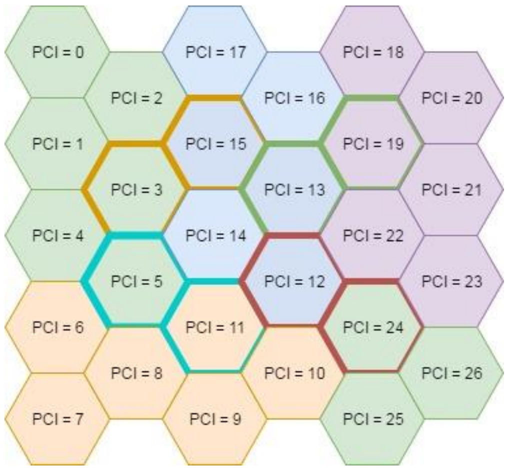


Figure 12. Example of PRS muting pattern with T_{REP} 4 and duty cycle 25%

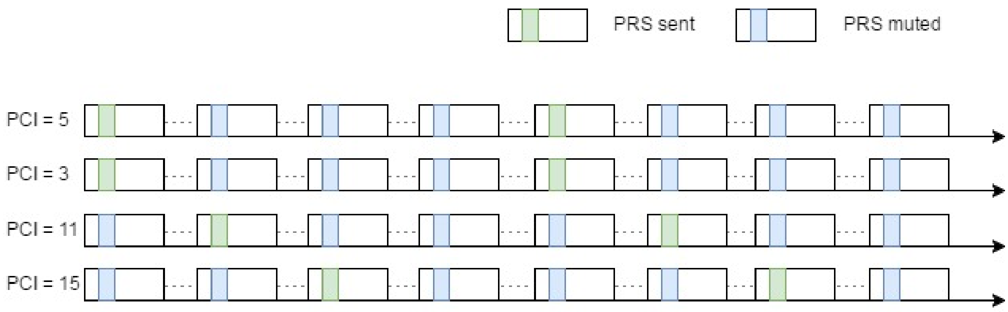


Figure 13. PRS muting example with several nodes

2.5 Simulation environment

The simulation tool used in this thesis is Matlab, developed by Mathworks. The name Matlab was originated from “matrix laboratory” since it was originally developed for matrix computation. Matlab integrates computation and visualization and can interact with programs written in languages such as

C, Fortran, C++ and Java. It is also one of the main choices for mathematical computation, simulation and prototyping. To help with the simulation, Matlab has its own block diagram environment called Simulink. This allows the user to visualize the simulation, and make the different elements interact with each other in a more intuitive manner [18]. For the purpose of this thesis, Simulink is a rather restricting tool. Coding in Matlab’s environment will then be the preferred choice during the development of the simulation environment for this thesis.

Matlab has also developed a number of toolboxes. Each toolbox has a collection of functions related to some particular application, and extend Matlab’s basic functionalities. There are toolboxes for signal processing, control systems, simulation, neural networks, amongst others. Their latest toolbox “LTE Systems Toolbox” provides almost any function needed for the simulation, study and evaluation of LTE networks [18]. This toolbox shall be purchased separately from Matlab, and therefore will not be used during the development of this thesis. Matlab’s signal processing toolbox, on the other hand, can be accessed by any student and has many useful functions (on a much lower level compared to the LTE Systems Toolbox) for modulation, processing and signal evaluation that will be valuable in the development of the simulation environment required for this thesis.

3. Method

After acquiring an overall knowledge on how positioning works in the network as well as the main characteristics of OTDOA, positioning signals and muting patterns, the methodology followed to study the effects of muting patterns in the network interference can now be explained. In section 3.1, the different elements of the simulation environment are described. An explanation on how each element works and why those elements are in the simulation while others are not included can also be found in this section. In section 3.2 the different muting patterns simulated in the thesis are described. The different scenarios where those muting patterns are implemented is explained in section 3.3. The different patterns are not only compared in terms of number of detected nodes but also on how they affect the SNR. How this is calculated is detailed in section 3.4.

3.1 Simulation Environment

To be able to assess the impacts of muting patterns in the interference between positioning signals, a simulation environment was needed. As previously stated in section 2.5, this simulation environment has been built using Matlab's coding interface with the help of functions from the signal processing toolbox. The aim of the simulation environment was to reproduce the behavior of the network, the transmission and reception of positioning signals, as well as the different factors that can alter the PRS while is being transmitted through the channel. But, how much of the network and its elements needs to be simulated in order to have a sufficiently detailed environment? A block diagram of the simulation environment can be found in the Annex 1.

3.1.1 Choosing the simulation environment

In order to show the behavior of the positioning signals in the network, how they interact with each other and how the different muting algorithms affect the overall interference, it was decided to implement a simulation environment in Matlab. There are several reasons behind this decision. Firstly, the thesis also developed for Ericsson by S. Nyberg [19] creates a network with several nodes and one user and assigns a cell ID to each node so that neighbor nodes do not have the same cell ID. This network was created in Matlab and can be reused as the base network in which to build on the positioning signals in this thesis.

In the same way, the work on this thesis can be later easily reused or modified. Having a well coded simulation environment, with well-defined functions and parameters will allow it to be reused in further studies. The parameters can easily be changed to fit the characteristics of any new studies and the muting algorithms used can be interchanged.

A well coded simulation environment will not only increase its reusability but has also helped with the simulations and testing in the studies performed in this thesis. The parameters and muting algorithms could be easily changed without the need of redoing all the calculations. This has made the simulation and testing process faster and less tedious, since several patterns have been simulated with several different parameters for each one of them.

The flexibility that characterizes a coded simulation environment is also an advantage over theoretical studies performed by Srinivasan et al. [6]. In addition to allow the study of different muting algorithms by only changing one of the many functions involved, it is easier to implement different functionalities which will allow the development of a more detailed environment that the one that can be achieved in a theoretical study.

3.1.2 The network

One of the first requirements for the simulation environment, is to have a network with a sufficient number of cells. For each eNB or cell, there should be a set of coordinates x and y that defines the position of that cell within the network, and a PCI or cell ID that will identify the cell. This can be implemented in a matrix, where each row will correspond to a cell and will have three columns: x coordinate, y coordinate and ID. To create such a network, it was decided to make use of the code developed by S. Nyberg [19]. This code creates a group of cells and assign PCIs to those nodes so that the network will be free of conflict. A free of conflict network will not have two neighbor cells with the same PCI. Since there are only 504 possible PCIs, within large networks the IDs will have to be reused. As an example, having neighbor cells with the same PCI will lead to conflicts during user handovers. The reason to use the code by S. Nyberg [19] is to have a network as close to reality as possible, rather than a perfect hexagonal-cell network. That code has been slightly changed to adapt to the parameters of the thesis. The network has been created using the function create_network.m which has been developed so that it calls the code done by S. Nyberg [19], and formats the output network so that it can be used in the simulation.

The next step is to place an UE in the network. In a real network, there would be several users, but only one user will be simulated in this environment. The reason behind that is that the signals of a user cannot affect the positioning signals being transmitted, since PRSs can only be interfered by other PRSs. Even if several users where undertaking the positioning process, the positioning signals would remain the same as the scenario with only one UE. The user has been placed randomly in the network, and is defined by a vector with two positions: x coordinate and y coordinate. This is done with the function create_UE.m. Figure 14 shows how the network would look like. The UE is represented with a red circle and the cells are represented with blue triangles.

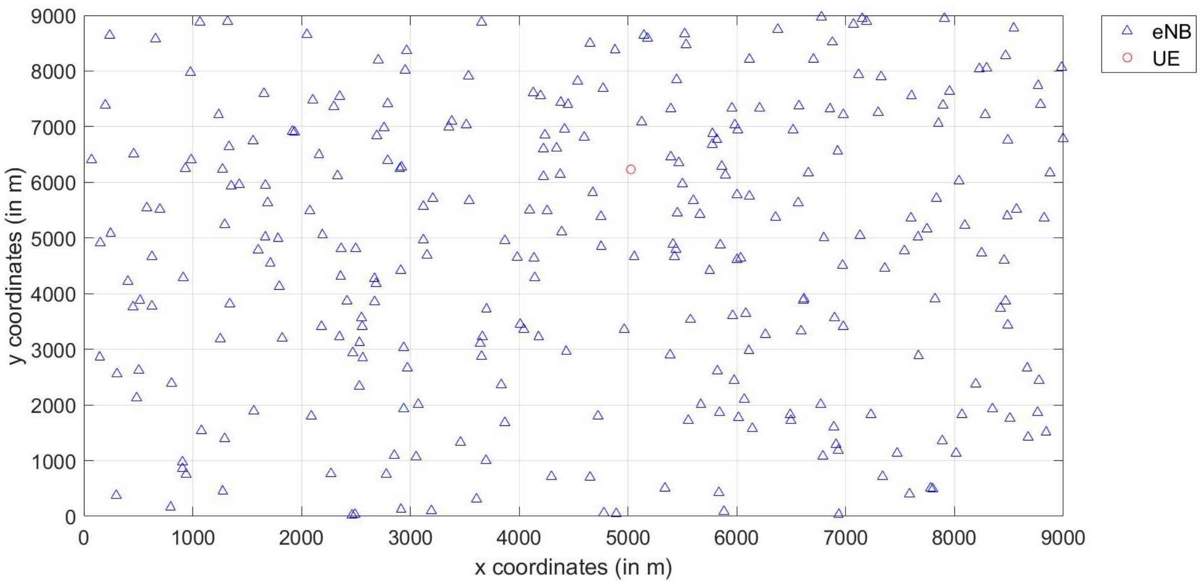


Figure 14. Example of dense-urban network of 81 km2 and 289 nodes with one UE.

3.1.3 Generating the PRS

Section 2.3 explains the mathematical equations needed to generate a PRS sequence. The generation of the positioning signal is standardized in 3GPP TS 36.211 [10]. In order to implement the positioning signal sequence in the simulation, the equations 2, 3, 4, 5 and 6 have been introduced in Matlab. This had previously been done by Zarrinkoub [20] for reference signals in general, the code has been reused and modified so it fits the parameters of the simulation of this thesis. The PRS sequence has been generated for only one antenna port, since PRS are transmitted only in port 6 and for two slots (one subframe). The obtained sequence is stored in a three-dimensional matrix which contains the correspondent QPSK symbols for the PRS of two slots (one subframe), seven symbols per slot and 2 times the bandwidth sequence elements. The PRS is the generated with the function prs_generator.m.

3.1.4 Mapping the PRS resources

Once the PRS sequence is generated, each QPSK symbol needs to be mapped to a number of resource elements within the slot. Each slot has 12 times the downlink bandwidth subcarriers. The bandwidth is expressed in multiples of the resource block size (Table 1). The resource block size is given by the number of subcarriers, 12 carriers in total, the bandwidth of each carrier is 15kHz, which gives a total size of 180 kHz per resource block.

PRS bandwidth

In MHz	In multiples of resource block size (180 kHz)
1.4	6
3	15
5	25
10	50
15	75
20	100

Table 1. Possible values for the PRS bandwidth.

Section 2.3 contains the equations needed to map the PRS resources as defined in 3GPP TS 36.211 [10]. Equations 7, 8, 9, 10 and 11 are introduced in the simulation. The simulation has only been done for normal cyclic prefix. In each resource block, 2 elements of the PRS sequence has been mapped, m and m+1. In order to verify the resources map obtained from the simulation, the parameters used can be introduced in an online simulator [21], which creates a graphical view of the PRS with the given parameters. Mapping the PRS resources is done with the function prs_mapper.m (Figure 15 and Figure 16).

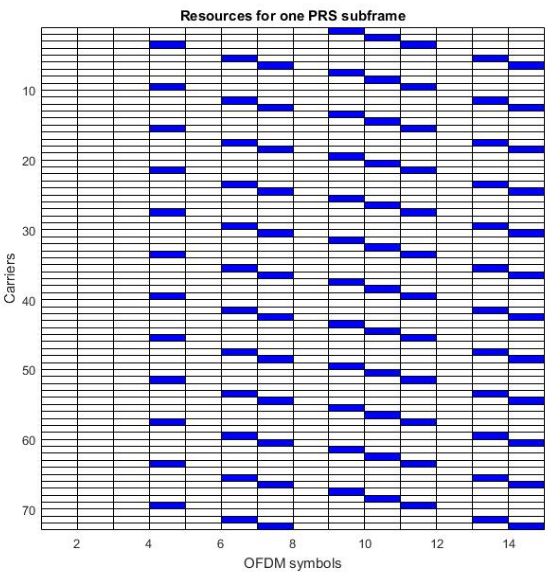


Figure 15. PRS resources mapped for PCI 0 and bandwidth of 6.

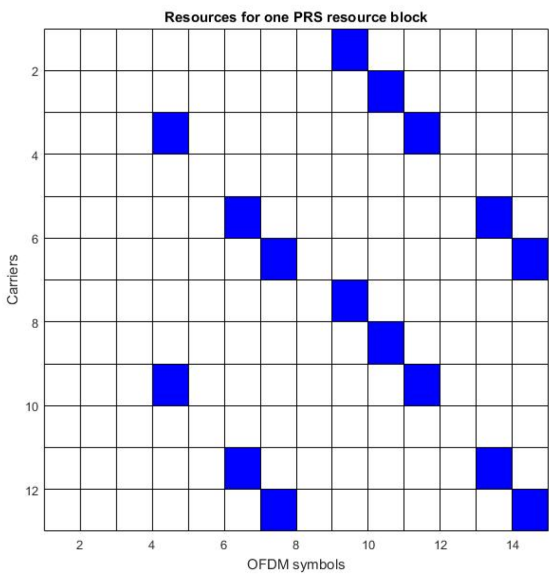


Figure 16. PRS resources mapped for PCI 0 and 12 carriers.

3.1.5 OFDM modulation

The mapped resource PRS sequence has to be modulated before being transmitted through the channel. The modulation chosen in the 3GPP TS 36.211 standard is OFDM. In order to build this modulator, the definition of OFDM modulation (Figure 17) has been followed. A general OFDM modulator code [22] has been modified since the encoder and the BPSK modulation has already been done in the generation of the PRS sequence and the resource mapping. Therefore, it is only needed to perform the IFFT of the sequence obtained from the resource mapping. Additionally, the OFDM modulated signal has also been amplified so that it meets the power requirements of a transmitted signal (around 10 watts [23]). The OFDM signal (Figure 18) is generated in the function OFDM_mod.m.

Figure 17. OFDM modulator block diagram.

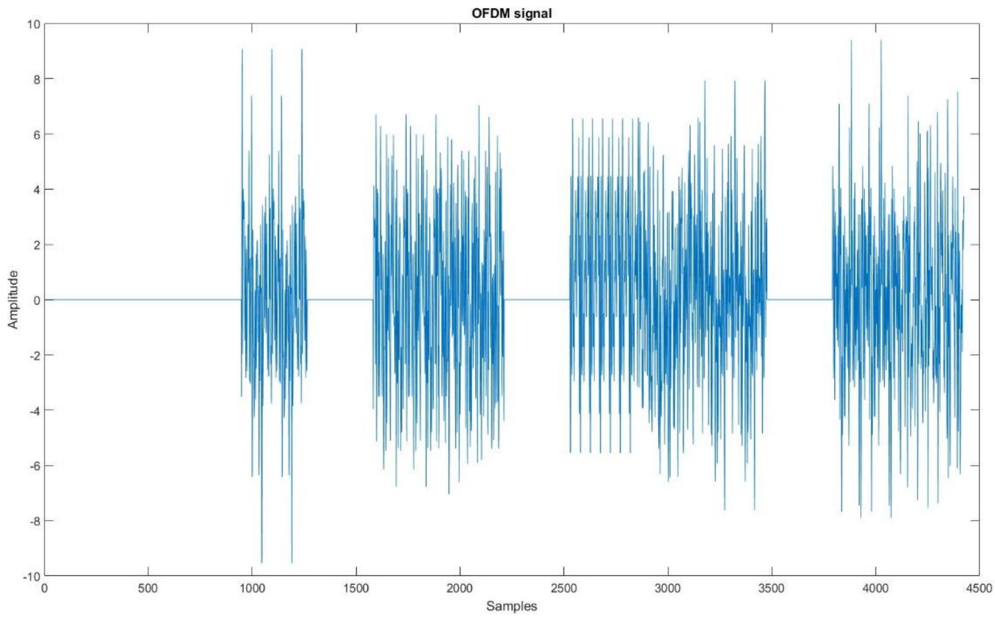


Figure 18. PRS signal modulated with OFDM.

3.1.6 The channel

During the transmission through the radio channel, positioning signals like any other signal, suffer from attenuation due to pathloss. The signal can lose strength just by being transmitted over a large distance, or due to obstacles that refract and reflect the signal, so when all this new versions of the signal arrive at the receiver together with the original signal, it attenuates the original signal. There are different models that have been created to predict pathloss and that have been proven to give values for the attenuation close to the values obtained in a real network. This models can be easily introduced in Matlab. The two models used in this simulation are the Log distance path loss model and the Hata model. Both models yield to similar pathloss values. The Log Distance Path Loss model is a generic model that can be used to predict the pathloss for different environments [24].

$$PL\ (in\ dB) = PL_{d_0} + 10nlog_{10}\frac{d}{d_0} \tag{17}$$

Where PL_{d_0} is the Free Space path loss at a reference distance d_0, with $d_0 < d$ and n is the path loss exponent, depending on the environment (Table 2).

Environment	Pathloss exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Table 2. Pathloss exponent n for different environments.

The Hata model is a model developed for urban areas and it is based in measurements taken empirically [25]. This model is valid for a signal frequency between 150 and 1500 MHz, a mobile station antenna height between 1 and 10 m, a base station antenna height between 30 and 200 m and a maximum distance of 10 km.

$$LP(dB) = 69.55 + 26.16\, log_{10} f - 13.82\, log_{10} h_B - C_H + [44.9 - 6.55\, log_{10} h_B] log_{10} d \quad (18)$$

$$C_H = 0.8 + (1.1\, log_{10} f - 0.7) h_m - 1.56\, log_{10} f \quad (19)$$

$$f(x) = \begin{cases} 8.29\big(log_{10}(1.54 h_M)\big)^2 - 1.1, & if\ 150 \le f \le 200 \\ 3.2\big(log_{10}(11.75 h_M)\big)^2 - 4.97, & if\ 200 < f \le 1500 \end{cases} \quad (20)$$

Where h_B is the base station antenna height, C_H is the antenna high correction factor and h_M is the mobile antenna height.
Adding the attenuation to the signal is done in the function add_pathloss.m.

The signals also suffer from delay that depends on the distance over which they are transmitted. Radio waves travel at the speed of light. Knowing this and the distance, the time delay can be calculated. This time delay is used as a fractional delay, added to the signal as fractions of an OFDM symbol. One symbol occupies a time of 66.7 µs [20]. The delay is added to the signal in the function add_delay.m.

Lastly, the signals also suffer from additive noise, in the form of white Gaussian noise which can be added in Matlab with the function awgn. For the purpose of the simulation, Gaussian noise will not be added, so that a fair comparison is made between the different signals and models simulated.

Another of the decisions made for the transmission of positioning signals in the simulation is that only one subframe of the PRS signal will be sent. This is enough, since the distances between the cells and the user that are being simulated are not long enough for the signal to experience significant delay. For a signal to be delayed a tenth of a subframe (0.1 ms) it would have to be transmitted over a distance of 30 km. The networks that will be simulated in this thesis will have a maximum distance between a node and a UE of 20 km. Therefore, sending just one subframe will give enough information for the signal to be correctly detected.

Finally, as stated in section 2.3, positioning signals could also be shifted on time with a subframe offset depending on the I_{PRS}. Since most of the operators choose the same I_{PRS}, the positioning signals will have the same shift, which means that they will be transmitted at the same time occasions. Even if the I_{PRS} were different for each operator, the nodes within a network would have the same I_{PRS}. Therefore, it has also been decided that the transmission of the PRSs would be synchronized, all the positioning signals will start being transmitted at the same time.

3.1.7 The receiver

Positioning signals are implemented so that they cannot suffer from interference from other signals from the network. PRSs can only have interference from other positioning signals (see section 2.3). Therefore, there is no need to simulate the behavior of other signals in the network. The positioning signals that arrive at the receiver can simply be added to each other in order to form the received signal. Therefore, the final received signal is the addition of all the PRS that arrive at the receiver, each one with its own delay and attenuation depending on the distance.

3.1.8 Detecting the signals

The received signal shall be compared with the sent signals in order to be able to determine if the UE has correctly received any or a specific sent signal. Calculating the level of similarity between two signals can be done using what is called cross-correlation, which is the convolution of the two signals to compare. During the convolution of two continuous signals, signal A slides through signal B as they multiply their amplitudes, therefore the cross-correlation value will increase until the two signals are completely lined up, and then decrease as signal A slides out of signal B. The higher the maximum value of this correlation is, the more similar two signals are. When the cross-correlation is normalized, its values will range from -1 to 1. When two signals are the same, the maximum value of the cross-correlation will be 1. Since the positioning signals are represented in Matlab not as a continuous function but as a discrete vector, the cross-correlation can be done in an easier calculation following the next equation:

$$(f * g)[n] = \sum_{m=-\infty}^{\infty} f^*[m]\, g[m+n] \tag{21}$$

In order to know if a signal has been detected by the receiver, the cross-correlation of each of the possible received signals with the actual received signal will be calculated. In the approach followed in this thesis, the cross-correlation value will not be normalized to one. The average level of noise will be calculated for each signal and the maximum value of the cross correlation will be compared to the noise level. If the value of the cross-correlation is above the noise level, the signal will be considered detected by the receiver.

3.2 Muting pattern algorithms

In this section, the different muting pattern algorithms implemented in the simulation environment are explained. The reason behind these methods and why is it believed that they will improve the interference between PRSs is also outlined.

3.2.1 PCI based muting pattern

Since two nodes with the same frequency shift will interfere each other's PRSs, making those nodes transmit at different times should solve the problem. A fairly simple way to do that, is to assign different muting sequences to those nodes, based on their PCI, since the frequency shift is obtained from the PCI number.

Having the desired muting pattern length T_{REP} and the duty cycle, the total number of sequences that are a combination of those factors can be obtained. The sequences are assigned to each node so that nodes with the same frequency shifts will have different sequences, as long as it is possible. Nodes with different frequency shifts can have the same muting sequence. Matlab can calculate all possible sequences by using the function nchoosek(). Then, each node can select one sequence out of all those possible sequences by using an index. This index is calculated as shown in equation 22 so that it gives the same index ($index_1$) to the first 6 PCIs (with PCI 0 to 5) and therefore they will have the same muting sequence ($sequence_1$). The next group of 6 PCIs (numbers 6 to 11) will all share the same index, and this index will be $index_1 + 1$ and the sequence will be $sequence_2$. Each group of 6 PCIs in ascending order will get a different index, until all possible sequences have been used. In that case, the next group of 6 PCIs will start with the first possible sequence and the sequences will be assigned again.

$$Number\ of\ possible\ sequences\ N = \frac{T_{REP}!}{\left(T_{REP} - (T_{REP} \times Duty\ cycle)\right)!} \tag{22}$$

$$index = mod(\lfloor PCI/6 \rfloor, N) + 1 \tag{23}$$

To illustrate this with an example, a muting pattern with $T_{REP} = 4$ and duty cycle = 0.5 has been selected. The total number of possible sequences with that parameter selection is 6. Then the sequences will be assigned with the help of the index (Table 3).

PCI range	Index	Muting Sequence
0 – 5	1	1100
6 – 11	2	1010
12 – 17	3	1001
18 – 23	4	0110
24 – 29	5	0101
30 – 35	6	0011 (End of all possible combinations)
36 – 41	1	1100 (Starting from the beginning)
42 – 47	2	1010
48 – 53	3	1001

Table 3. PCI based muting pattern example.

This can also be done without the need to calculate all possible combinations for each node, and select one of those based on the PCI. Each cell can calculate only the muting sequence that corresponds to it by using the algorithm proposed by Srinivasan et al. [6]. This algorithm still uses the index as calculated in equation 23, but returns only one muting sequence, without the need of calculating all possible combinations. The algorithm has been implemented in this thesis, with some modifications to allow it to perform correctly. Both approaches, calculating all possible combinations and choosing one versus calculating only the needed sequence, yield to the same results and assign the sequences in the same order.

3.2.2 Random muting pattern

PCI based muting algorithms are the straight forward choice for muting patterns. If the probability of interference of two PRSs depend on the PCI (as explained in the section above), then the muting pattern should be also chosen depending on the cell ID. An easier approach is to allow each node of the network to randomly choose a muting sequence within a given muting pattern. The length and duty cycle of the muting pattern will be set for the whole network and each node will randomly choose a sequence with those parameters.

For the implementation of this pattern, the algorithm developed for PCI based muting can be reused. In this case, the index will not be calculated in function of the cell ID, but rather be chosen as a random number between 1 and the total number of possible muting sequences.

Since the cell ID will not be taken into account, the results obtained with this algorithm are expected to be worse and more unpredictable. It is expected that the user will not be able to detect as many nodes and that this number will not be constant, but rather change depending on the random indexes selected.

3.2.3 Neighbor based muting pattern

PCI based muting algorithms are designed for a network with perfect PCI planning. In these type of networks, two neighbor nodes will not have the same cell ID and will not have the same frequency shift. Is in these networks where the best results for PCI based muting can be observed.

Deployed networks do not have a perfect PCI planning. The cell IDs are given to avoid as much as possible that two neighbors have the same ID since this can affect handovers. But there is nothing specified for avoiding neighbor cells with the same frequency shift when assigning the cell IDs. Therefore, in a deployed network, there will be neighbor nodes with the same frequency shift, which means that it cannot be expected that PCI based muting will give its best results.

It seems important then, to not only take into account the cell ID but also the frequency shifts that the neighbors have in order to get the best results possible when implementing a muting pattern. This is the new muting pattern algorithm implemented in this thesis, that is compared against PCI based muting in order to study the improvement in the number of heard nodes.

For this algorithm, the nodes will be assigned a preliminary muting pattern following the PCI based muting. After this, it will be checked that nodes that have a relation of neighbors and have the same frequency shift do not have the same muting sequence. These neighbor relations are stablished when the network is created, based on the distance and a certain relation probability. This relationship matrix has been calculated by S. Nyberg [19]. If nodes that have a relation have the same muting sequence, then one of the nodes will be assigned a new muting sequence. For this assignment, the muting sequences of the neighbors of the node will be taking into account and also the neighbors' neighbors and the node will be assign a muting sequence different from all those, if possible. This algorithm will be run until no more nodes can be changed.

3.3 Scenarios

3.3.1 Dense Urban

A dense urban scenario can be found in any modern big city, being the main studied examples big cities in Europe and Asia. These scenarios have in common several characteristics such as the existence of many buildings, most of them tall, with 4 or more stories. This will make almost impossible for the UE to have a direct line of sight with any cell. The multipath attenuation in this kind of environments will be high, since the signals will be reflected by the many buildings and arrive to the user through several paths. Another characteristic of a dense urban scenario is the high population that can be found in these cities. The number of UEs will be higher than in any other scenario and as a result, the number of signals will also be higher. A higher number of signals implies a higher interference between them. The high number of users brings the need to have more cells to be able to handle the increasing amount of connections. These cells will be closer together with a distance between them of 400 m – 800 m, increasing the amount of interference between cells. Any dense urban scenario therefore, will have a high amount of connections and cells in a moderately big area, resulting in an increased interference. Due to this high interference, calculating the position of an UE with the needed accuracy is difficult.
The dense urban network has been created in the simulation environment by reusing the code by S. Nyberg [19]. As explained in section 3.1.1, the network is created by placing a number of cells in random positions inside a given area. The PCIs will be assign so that no neighbor nodes will have the same PCI, but they can have PCIs with the same frequency shift, which is not optimal from an

interference between PRSs point of view. The PCIs can be reused within the network as long as neighbor cells have different PCIs.

3.3.2 Hexagonal cell division

A representation of the network with each cell as a hexagon and equidistant to each other is the most widely used scenario for studying networks. In a real deployment, the cell shape is closer to a circle. But when taking into account overlapping from different cells, the final shape is similar to a hexagon. The distance between cells might not be equidistant in a deployed network. Some areas inside the same environment type might require more cells than others. The size of the area covered by each cell might be different. In the recently developed heterogeneous networks, there are picocells, microcells, femtocells, working together all with different coverage areas. Therefore, the ideal equidistant hexagonal cellular network might not be as close to what is being deployed as before, but it is still the model used when theoretically studying any aspect of a network. Therefore, this scenario will also be simulated and compared with the non-hexagonal scenarios.

The function create_ideal_network() creates the hexagonal equidistant cells in the simulation environment. Each cell is positioned as the center of the hexagon with the same distance to its neighbor cells. The positions of the cells are not random anymore, but carefully calculated to represent a perfect hexagonal cell division. Additionally, the PCIs in this scenario will be assigned so that no neighbor cells will have PCIs with the same frequency shift, which will help reduce the interference between PRSs. For this particular network, there will not be any PCI reuse.

3.4 Comparing muting patterns

The performance of each of the muting patterns will be assessed and compared between them to be able to determine which one presents the best results. The muting patterns will be compared in terms of the number of detected nodes in the network. They will also be compared in terms of the SINR per signal.

3.4.1 Detected nodes

The positioning process is directed by the positioning server. It is the server who executes the positioning calculations and who provides the user with the information needed to measure the time of arrival from different signals. The server will give the user a list with information about the user’s 72 closest neighbors. The nodes in this list are arranged in a preference order, from the one which is most important to measure to the one that is least important. The user’s task is then to measure as many of the nodes in that list as it can. Since this list and the preference order that the server sets changes from node to node and network to network, every possible scenario cannot be covered. Also, information on the server’s exact behavior has not been found. Therefore, it is concluded that the more nodes the user is able to detect in general the better, since it is difficult to know what the decision of the server will be in each case.

This is why the performance of the muting pattern will be assessed by the number of detected nodes, and it will be considered that the higher the number of detected nodes is, the better the performance of the muting pattern.

3.4.2 Signal to Interference and Noise Ratio

The main purpose of muting patterns is to lower the overall number of positioning signals being sent at the same time to lower the interference. This not only means that more cells will be detected but also that the overall signal to interference and noise ratio will be higher. Having a higher SINR allows the user to be more sure of the correct detection of the nodes, since the received signals will have a higher power value compared to the value of the interfering and noise signals. A higher SINR improves the reliability of the detection process and therefore of the positioning process.

The muting pattern will then be compared in terms of the signal to interference and noise ratio of the detected cells. Having a higher SINR means that the performance of the muting pattern is better.

4. Results

Following the methodology previously described, a series of simulations where carried out and the results obtained are shown in this section. For each simulation one of the possible muting pattern algorithms has been implemented in one of the proposed scenarios. The selected muting pattern algorithms and scenarios as well as the simulation environment have been previously described in section 3. The parameters used for each simulation will be detailed and the results obtained will be explained with the help of graphs of the network and UE and the detected nodes.

4.1 Number of detected cells

For every simulation of an urban dense scenario, the network created has an area of 81 km2 where 289 cells have been placed. The UE is also placed randomly for each repetition of the simulation. In the case of a random network, the eNBs are placed randomly inside the created area. Following the planning of any deployed network, no neighbor cells will have the same ID but they can have the same frequency shift. If the simulated network is an hexagonal ideal network the cells will be placed so that they are equidistant to each other, so each cell represents the center of each hexagon in the network. The cells follow a perfect PCI planning where no neighbor cells will have the same PCI nor the same frequency shift.

4.1.1 No muting

In a no muting scenario, no muting patterns are used. Simulating this scenario is important to be able to compare with muting scenarios, and study how much any muting pattern improves the interference situation and how many more cells the UE is capable to detect.

In the random network simulation the UE can detect a mean of 7 cells. In a deployed network there are no neighbor cells with the same PCI, but they can be several non-neighbor cells with the same cell ID. This is the case on the simulated random network. Cells with the same PCI will have the same positioning signal and the same muting pattern. Therefore the user can not be sure from which cell is the signal that has detected, since it could be coming from more than one node and this will translate in errors in the positioning calculations. One suggestion to lower this type of conflicts is to take into account the PCI of the neighbors when assigning the muting sequence to each cell. This pattern has been described in section 3.2.3. But it does not entirely fix these cell ID conflicts since a cell only has information about its neighbors, therefore if there are one or multiple non-neighbor cells with the same ID it will not be known by the cell.

Since the random network simulated in this thesis has several cells with the same ID there will be several of the previously explained cell ID conflicts. Therefore, the results are also presented in terms of the number of detected nodes with no conflict, where nodes with the same PCI that transmit with the same muting sequence are not taken into account. For the case of no muting the number of detected nodes without conflict lowers to 1. In figure 19, the number of detected nodes is represented. Following the same format as previous graphs, the UE is marked as a red circle, the different cells are blue triangles and when a cell is detected its blue triangle will be colored in with light blue.

In the simulation of a hexagonal network the UE can detect a mean of 3 cells (figure 20). Detecting a higher number of cells with no conflict compared to a random network is to be expected since a hexagonal network is the ideal deployment. Also it has been done following a perfect or ideal PCI planning. All this improves the detection of cells by the user. But this cannot be deployed in a real environment, therefore it is expected that a deployed network or the random network simulated in this thesis will result in a worst detection than the one obtained in the hexagonal network.

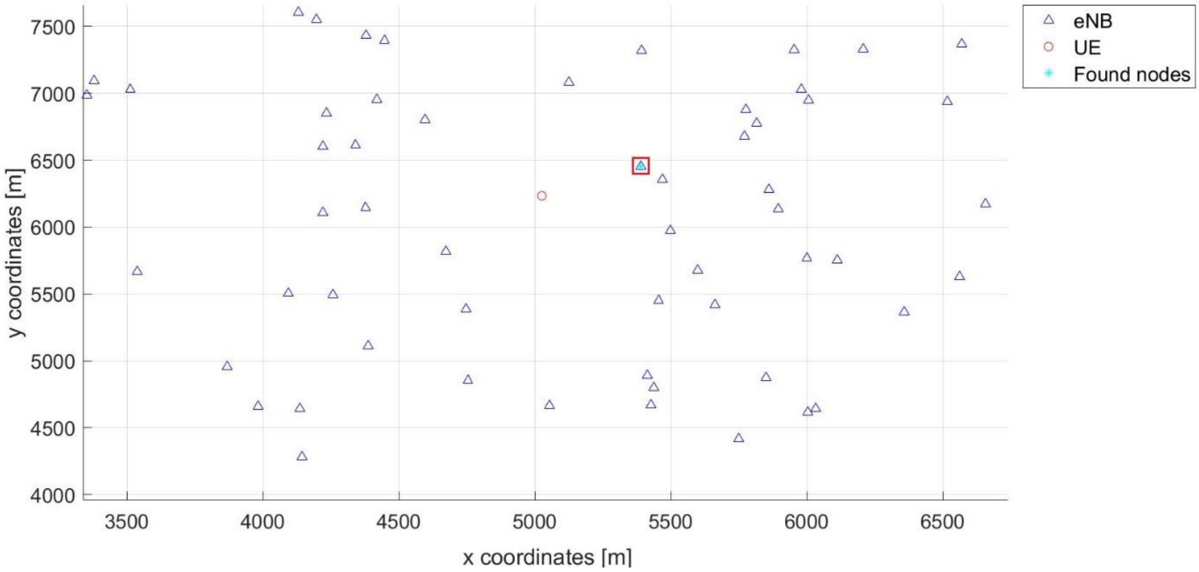


Figure 19. Nodes detected with no conflict in urban dense, random cells, no muting simulation

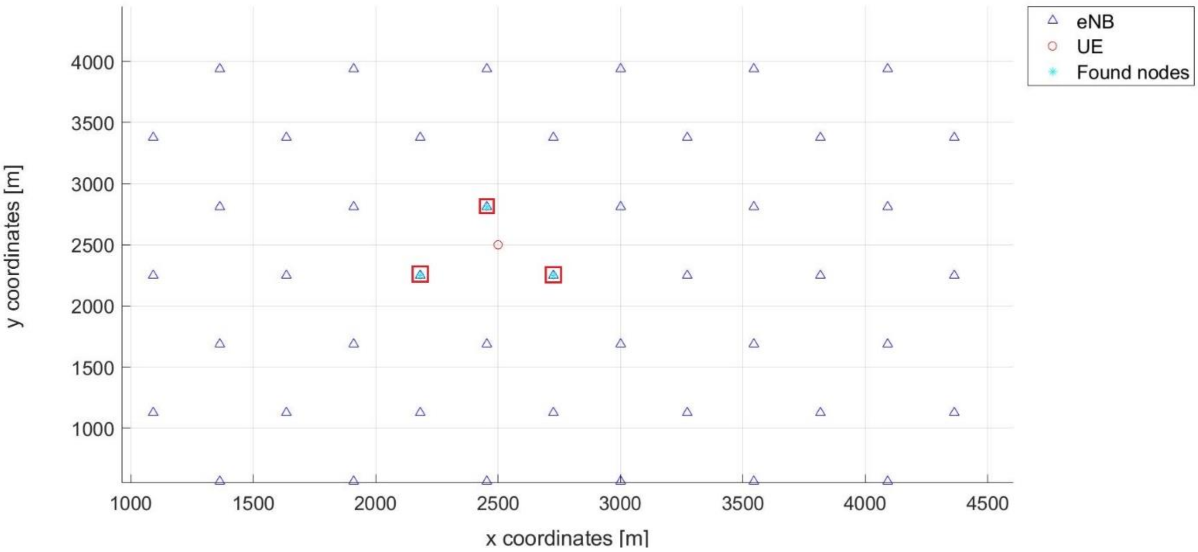


Figure 20. Nodes detected in urban dense, hexagonal cells, no muting simulation.

4.1.2 PCI based muting

In the simulations with PCI based muting pattern, the algorithm explained in section 3.2.1 has been implemented. Different values of T_{REP} and duty cycle will be assigned with the intention of comparing them and possibly find some rules or guidelines on which parameters to use to achieve the best results in terms of interference. For simplicity, a name has been assigned to each possible combination of T_{REP} and duty cycle. The assigned names can be seen in table 4.

Pattern name	T_{REP} (Length)	Duty cycle
A1	4	0.25
A2	4	0.5
A3	4	0.75
B1	8	0.125
B2	8	0.25
B3	8	0.5
B4	8	0.75
C1	16	0.0625
C2	16	0.125
C3	16	0.25
C4	16	0.5
C5	16	0.75

Table 4. Name for the possible combinations of T_{REP} and duty cycle

The theoretical studies on PCI based muting where initially done in a hexagonal network where the cell IDs where assigned following a perfect PCI planning so that no neighbor cells would have IDs with the same frequency shift. It is in this type of network where PCI based muting gives its best results. It is interesting then, to simulate how would this solution behave in a network which characteristics are closer to those of a deployed network. Initially, the number of detected nodes in the random network seems to be higher than the number of detected nodes in the hexagonal network (figure 21). But when taking into account only the cells that have been detected without any conflict it can be seen PCI muting performs significantly worst in the random network compared to the hexagonal network. This is to be expected, since the random network is not following a perfect PCI planning, therefore in this particular network, there will be multiple cells with the same ID that, following the algorithm that assigns the muting sequences, will have the same muting sequence. The receiver will not be sure of which of the two cells has detected. Due to this, as it can be seen in figure 21, the difference between the number of nodes detected and the number of detected nodes with no conflict is considerable, being this last one much lower than the former.

As far as comparing the different combinations of T_{REP} and duty cycle, it can be inferred from figure 21 that the combinations that result in a higher number of detected nodes are of length 16, with duty cycle 0.0625, 0.125, 0.25 and 0.5 followed by those of length 8 with duty cycle 0.125 and 0.25.

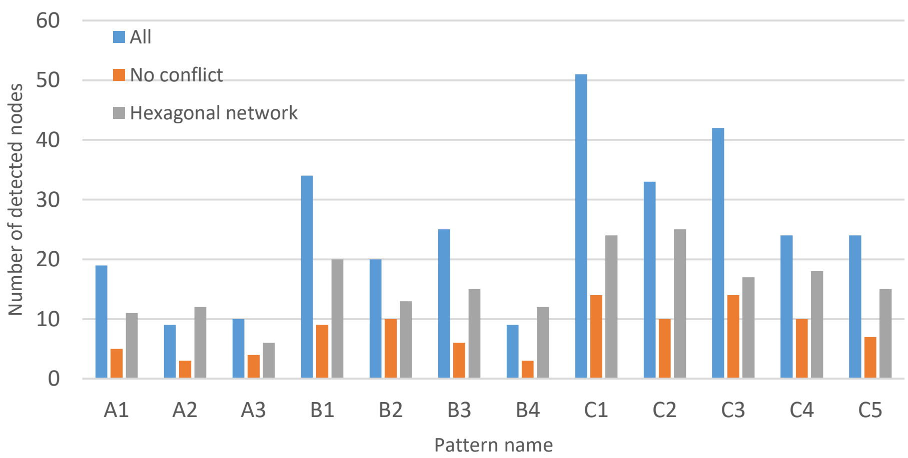


Figure 21. PCI based muting, number of detected nodes comparison

Figures 22 to 27 show the number of detected nodes both for a random network and a hexagonal network for selected values of T_{REP} and duty cycle. The number of detected nodes for all the possible combinations of T_{REP} and duty cycle can already be seen in figure 21. Figures 22 to 27 aim to give a better understanding of which cells exactly have been detected. The UE is represented as a red circle, the cells are represented with a dark blue triangle and if a cell has been detected the triangle will be colored in with light blue. The user is able to detect most of the time those cells that are closer. Occasionally, the user detects a cell that is rather far from its position, as it can be seen in figure 23. In the hexagonal network, PCI muting allows the user to detect most of its closer cells, whereas in a random network the detected cells are not necessarily those closer to the user.

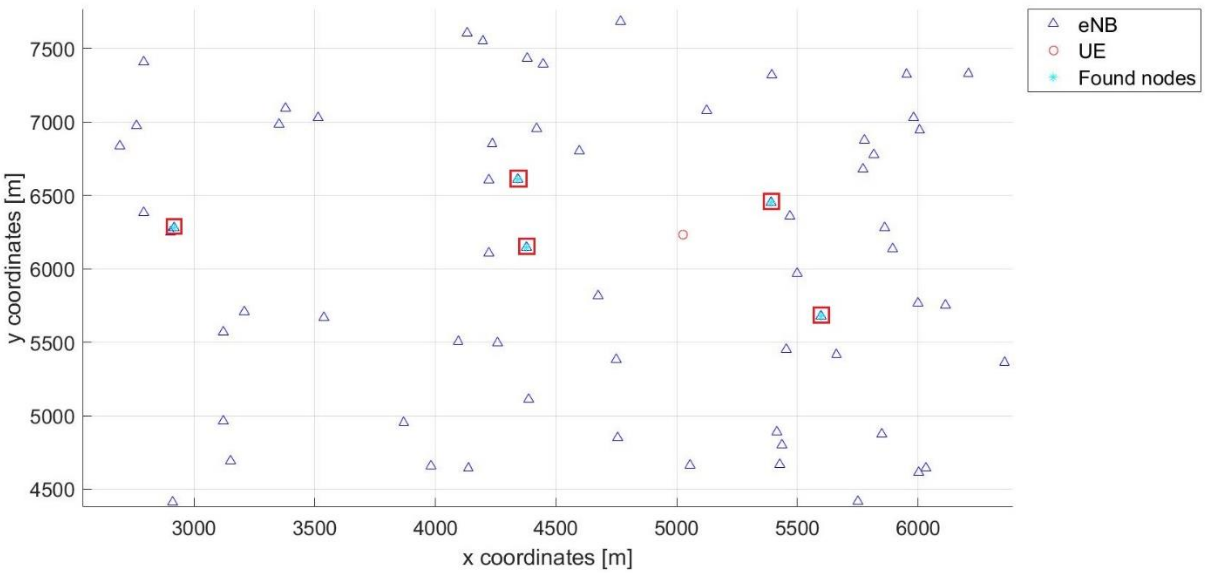


Figure 22. Random network, no conflict, PCI muting. T_{REP} 4, duty cycle 0.25

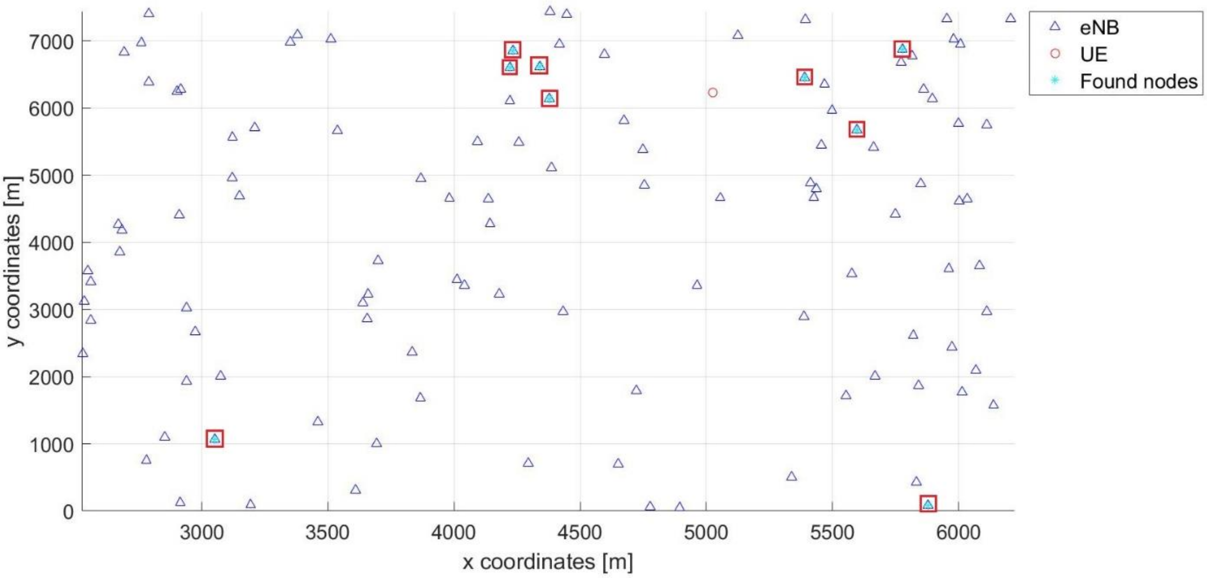


Figure 23. Random network, no conflict, PCI muting. T_{REP} 8, duty cycle 0.125

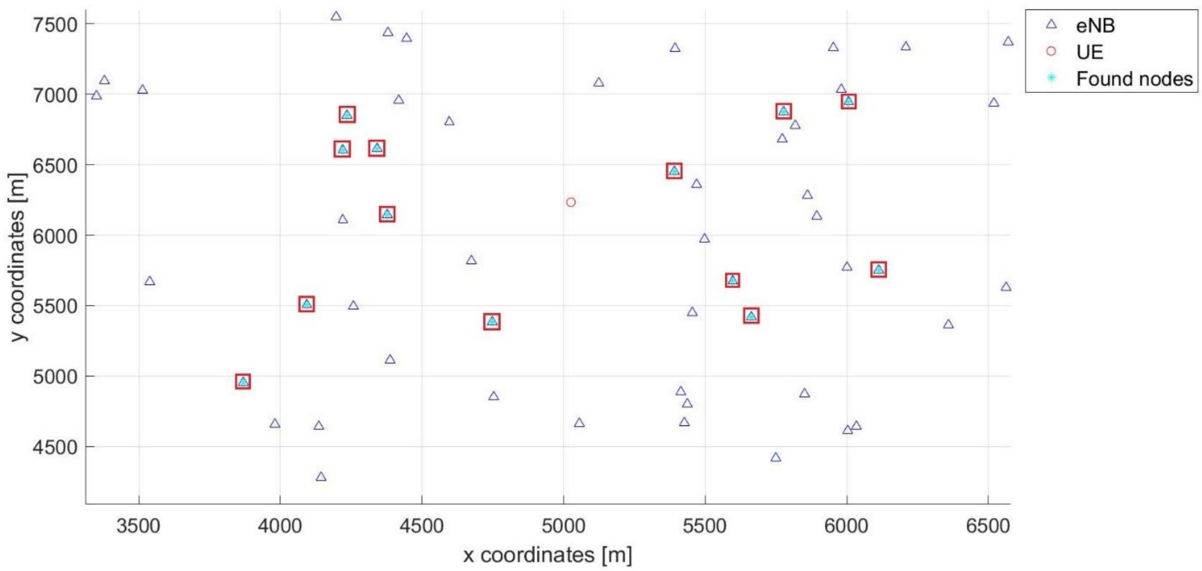


Figure 24. Random network, no conflict, PCI muting. T_{REP} 16, duty cycle 0.0625

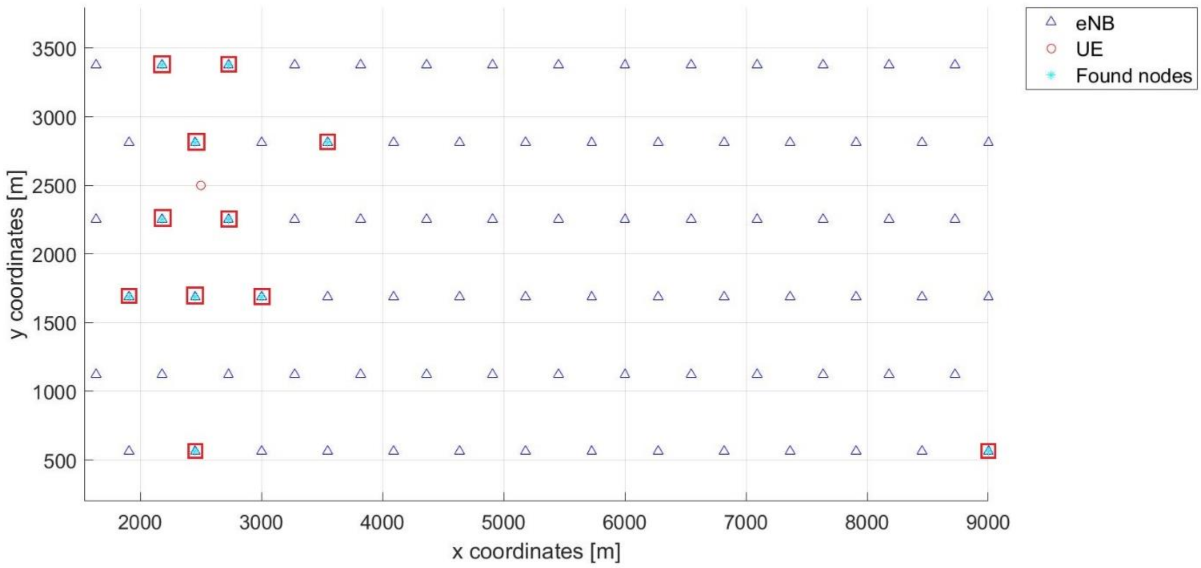


Figure 25. Hexagonal network, PCI muting. T_{REP} 4, duty cycle 0.25

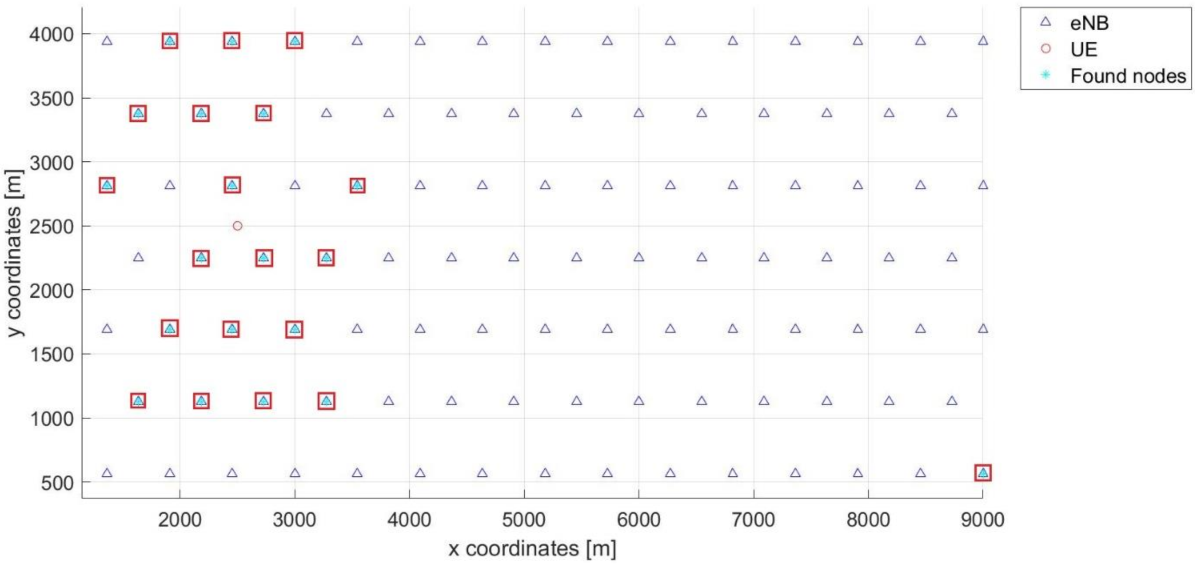


Figure 26. Hexagonal network, PCI muting. T_{REP} 8, duty cycle 0.125

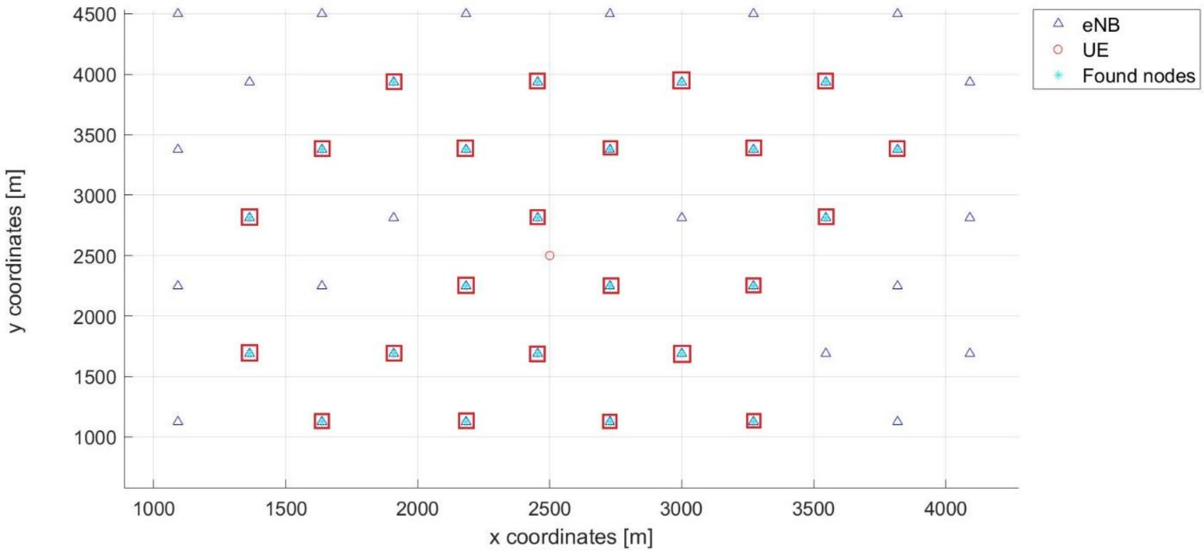


Figure 27. Hexagonal network, PCI muting. T_{REP} 16, duty cycle 0.0625

4.1.3 Random muting

In the simulations with randomly assigned muting pattern, the algorithm suggested in section 3.2.2 has been implemented. Once again, different values of T_{REP} and duty cycle will be assigned with the intention of comparing them and possibly find some rules or guidelines on which parameters to use to achieve the best results in terms of interference.

As its name indicates, random muting is characterized by assigning muting sequences to the different cells in an aleatory way. Therefore, for the same network, the number of detected nodes will vary every time the algorithm is run as opposed to PCI muting and neighbor based muting that for the same network will give the same number of detected nodes every time. Even though with random muting the number of detected nodes will change from simulation to simulation within the same network, it remains quite stable, only changing by 2 to 3 cells. The random character of this algorithm rather than representing a problem actually helps lower the number of nodes in conflict. As it can be seen in figure

28 the number of overall detected nodes is just barely higher than the number of detected nodes without conflict. When using PCI muting nodes with the same cell ID would be assigned the same muting sequence. With random muting, the probability that cells with the same ID are assigned the same muting sequence is quite small. When comparing this algorithm with the results obtained for PCI muting in a hexagonal network it can be seen in figure 28 that they perform quite similarly giving better results than PCI muting in a random network.

Out of all the possible combinations of T_{REP} and duty cycle, the ones that give the best results are length 16 and duty cycle 0.0625 and 0.125 and length 8 and duty cycle 0.125.

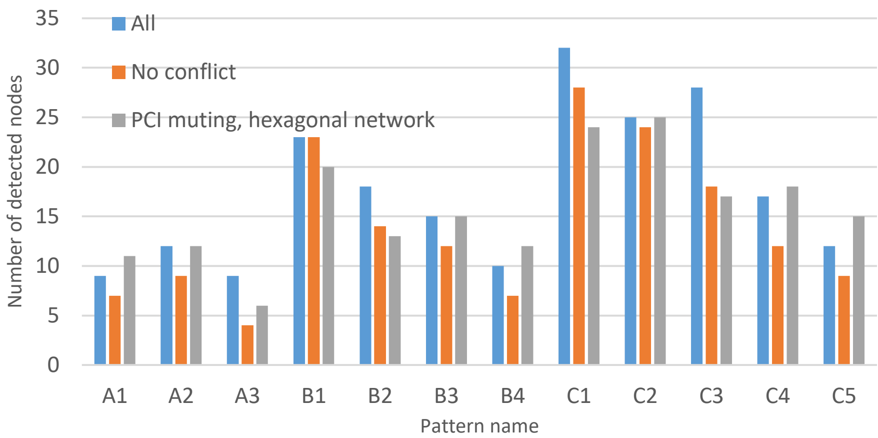


Figure 28. Random muting, number of detected nodes comparison

Figures 29 to 31 show the detected nodes for the same combinations of T_{REP} and duty cycle selected in PCI muting. As it can be seen the behavior of random muting is similar to PCI muting when this last one is used in a hexagonal network since it is able to find most of the nodes closer to the user.

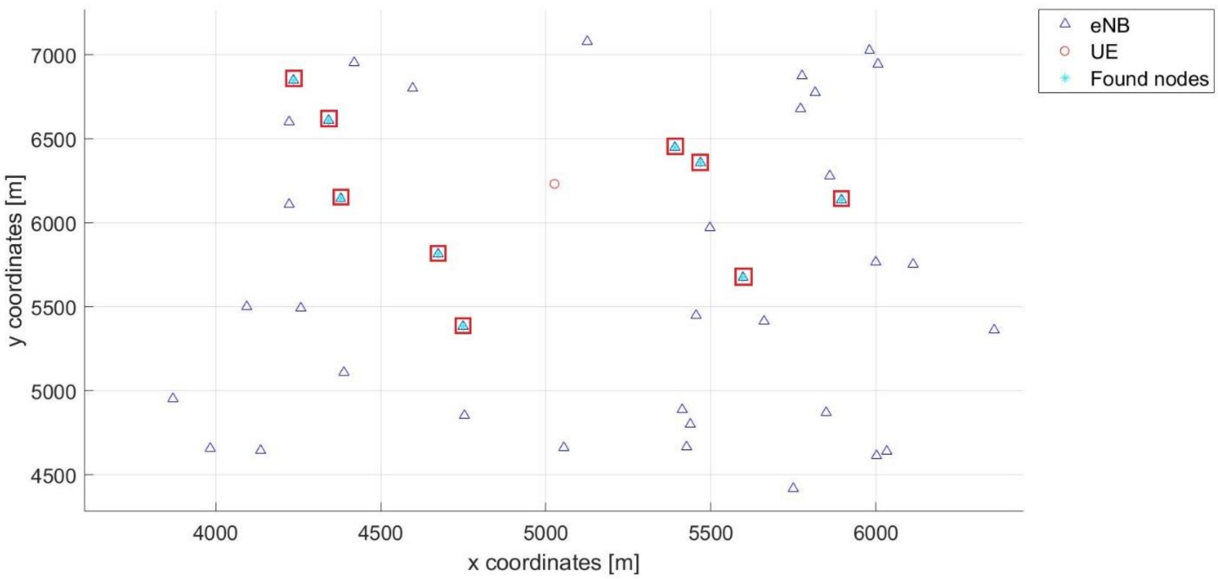


Figure 29. Random network, no conflict, random muting. T_{REP} 4, duty cycle 0.25

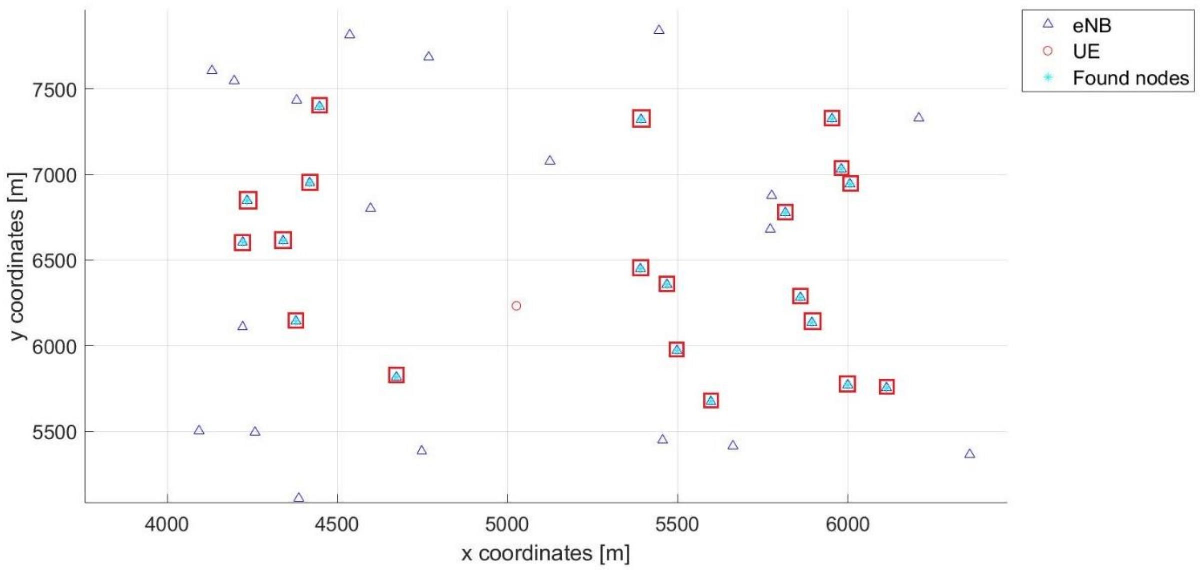


Figure 30. Random network, no conflict, random muting. T_{REP} 8, duty cycle 0.125

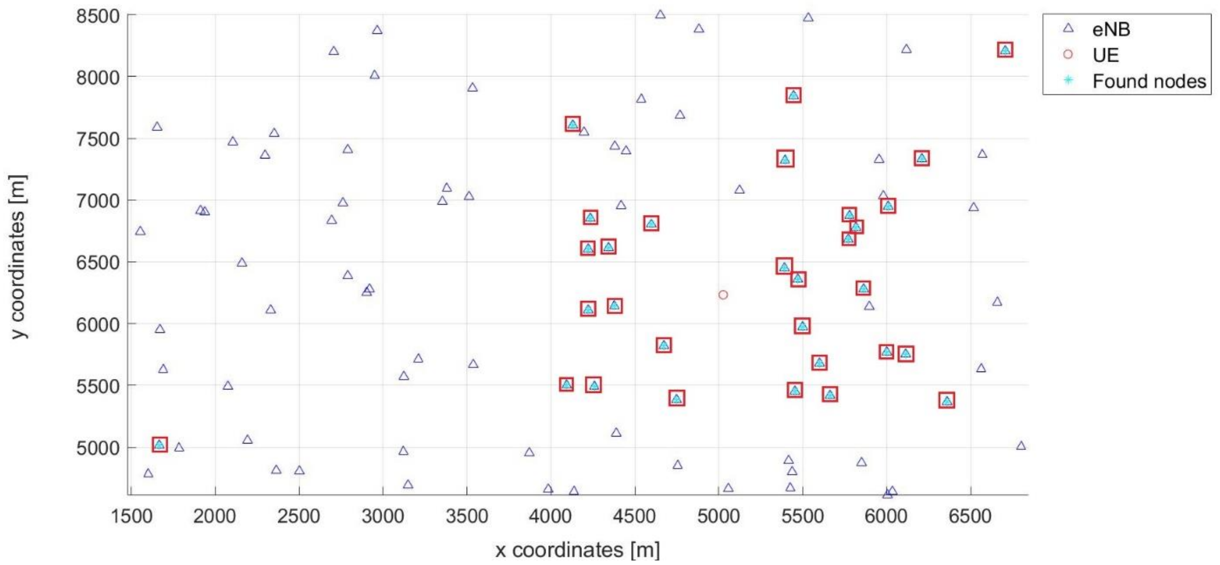


Figure 31. Random network, no conflict, random muting. T_{REP} 16, duty cycle 0.0625

4.1.4 Neighbor based muting

The algorithm explained in section 3.2.3 has been implemented as well as different combinations of T_{REP} and duty cycle. With the results of these simulations it can be assessed whether this new pattern improves the existent PCI based muting and random muting patterns.

One of the main problems of not having a network with perfect PCI planning is that neighbor cells might end up having the same frequency shift and their signals will therefore interfere each other, lowering the SINR and the probability of correctly detecting the cells. In order to fix this, a neighbor based muting pattern was proposed where the neighbor's muting sequences will be taken into account to make sure that every neighbor has a different muting pattern. This was expected to improve the results previously achieved with the PCI muting algorithm. But the neighbor based muting algorithm has ended up performing quite similarly to the PCI muting algorithm. The number of overall detected nodes is significantly higher than the number of detected nodes with no conflict as it can be seen in figure 32.

In a similar way to PCI muting, the combinations of T_{REP} and duty cycle that offer the best results as far as the number of detected cells are length 16 and duty cycle 0.0625, 0.125, 0.25 and 0.5 as well as length 8 and duty cycle 0.125 and 0.25.

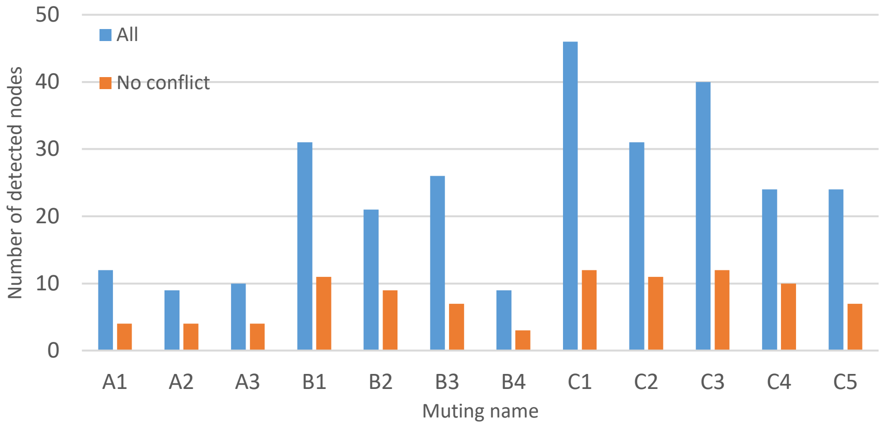


Figure 32. Neighbor based muting, number of detected nodes comparison

Once again, the detected nodes for the same combinations of T_{REP} and duty cycle previously selected for PCI muting are shown in figures 33 to 35. It can be seen that the neighbor based muting pattern has a similar behavior to the PCI muting as far as number of cells detected and which cells have been detected.

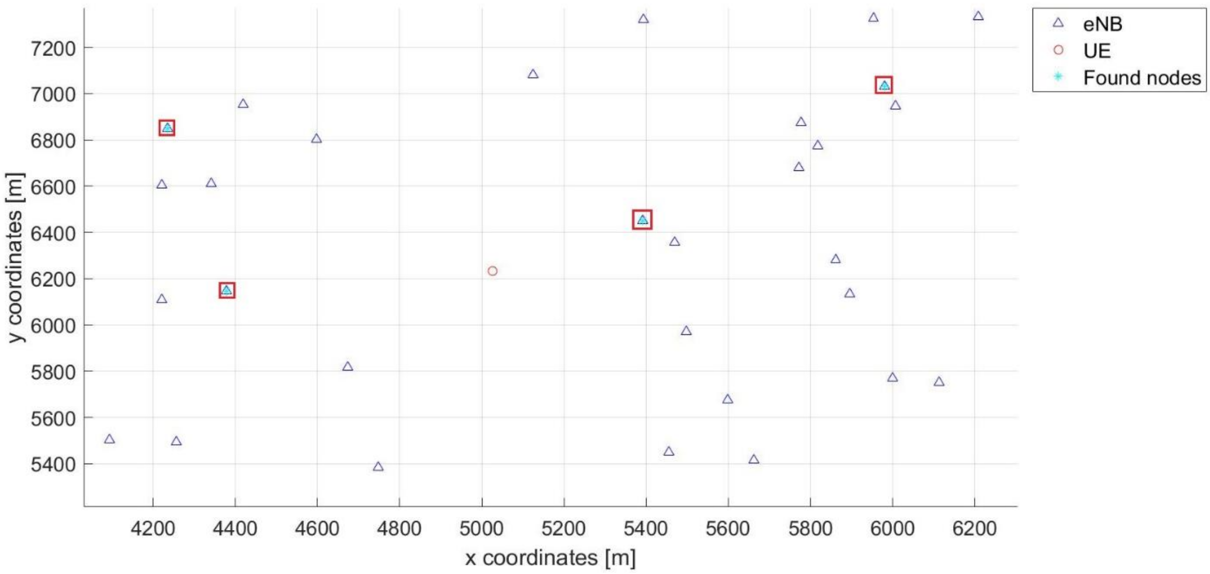


Figure 33. Random network, no conflict, neighbor based muting. T_{REP} 4, duty cycle 0.25

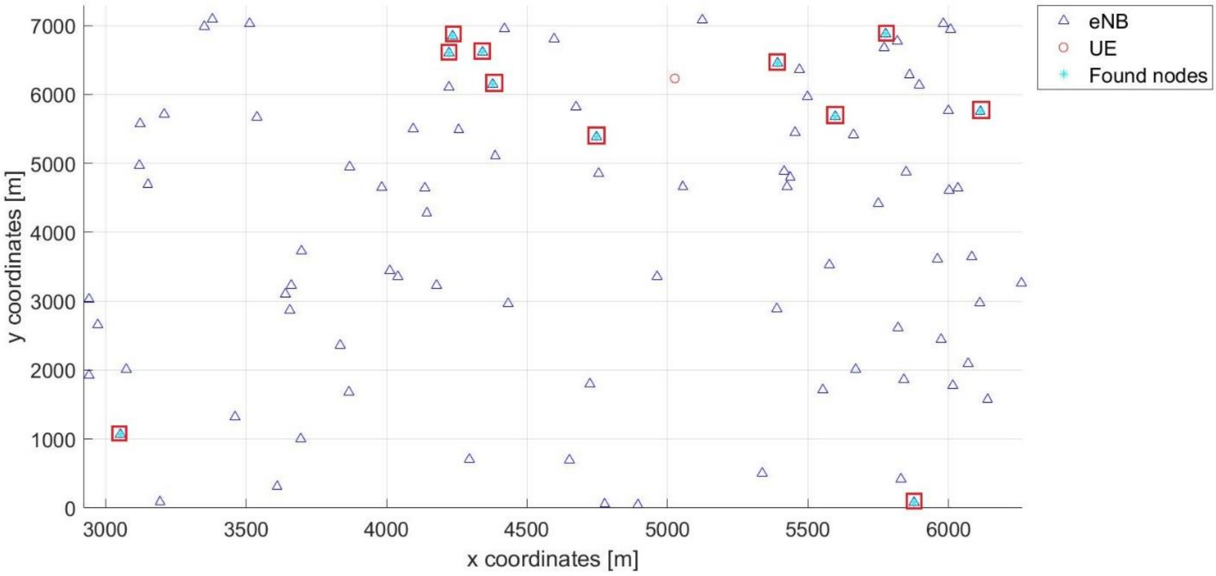


Figure 34. Random network, no conflict, neighbor based muting. T_{REP} 8, duty cycle 0.125

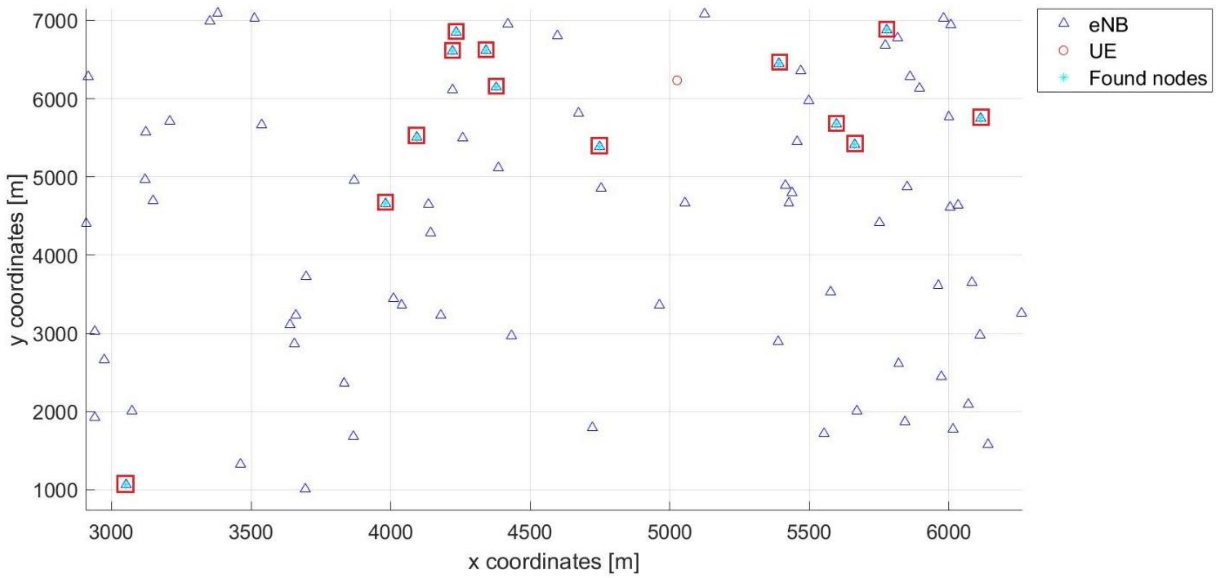


Figure 35. Random network, no conflict, neighbor based muting. T_{REP} 16, duty cycle 0.0625

4.2 SINR achieved

In order to fairly compare how the different muting patterns affect the SNR of a signal, the signals transmitted from 2 nodes that are detected in every simulation have been selected. The selected nodes will be the same for all the different simulations and muting patterns so it can be seen how the different patterns affect the same signal. The two nodes have a distance to the user of 424.6 m and 653.9 m, respectively. The results from the SINR calculations can be seen in figures 36, 37 and 38.

For PCI muting, the maximum value of SINR for both signals is achieved with the combinations of length 16 and duty cycle 0.125 and 0.25. For random muting, the maximum SINR for signal 1 and 2 is obtained in patterns with length 16 and duty cycle 0.0625, 0.125 and 0.25. Finally, the results obtained with the neighbor based pattern are quite similar to the ones of PCI muting, where the highest SINR value for both signals is achieved with a muting pattern of length 16 and duty cycles 0.125 and 0.25.

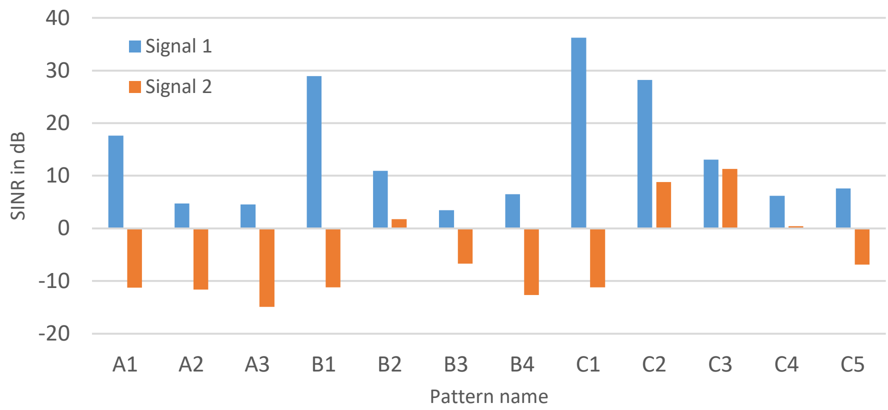


Figure 36. PCI muting, SINR for signals 1 and 2

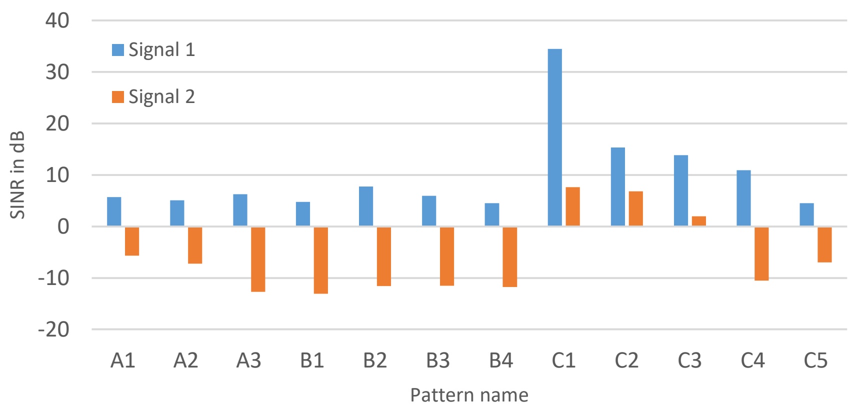


Figure 37.Random muting, SINR for signals 1 and 2

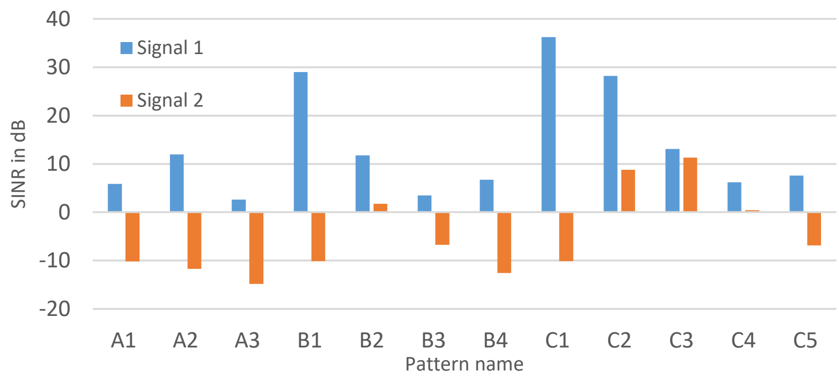


Figure 38. Neighbor based muting, SINR for signals 1 and 2

5. Discussion

A comparison of the obtained results will be done in section 5.1. Some guidelines will be extracted on how to choose a muting pattern and which are the ones that allow the UE to detect the most nodes. Section 5.2 will describe briefly the future work that can be done in relation with muting patterns and positioning. Finally, as a way to summarize the results obtained in this study, the answers posed in section 1.3 will be answered.

5.1 Results

In this section the results obtained from the simulations will be compared and discussed. Some general ideas will be drawn on which muting pattern or patterns give the best results and why. Characteristics of these muting patterns will be described and their advantages will be discussed.

5.1.1 No muting versus muting

When comparing networks where no muting has been implemented with networks where some kind of simple muting pattern has been deployed, it is easy to see that muting improves greatly the interference and allows the UE to detect more cells. When no muting was applied, the UE could detect 7 nodes, but this number was lowered to 1 if the nodes that can produce conflicts in the detection are not taken into account. As it can be seen in figure 39, most of the PCI based muting patterns can detect more than 7 nodes and they all detect more than 1 node. Being able to detect more nodes will help to select a better geometry of the measurements (as explained in section 2.2.1) which will improve the accuracy on the positioning measurements. The fact that muting patterns improve the accuracy of OTDOA cannot be refuted.

5.1.2 Overall comparison

When initially comparing all the possible combinations of each of the different muting algorithms previously described, as far as the overall number of heard nodes, it can be seen in that PCI muting and neighbor based muting perform quite similarly. With the use of these two patterns the user is able to detect a higher number of nodes that with the use of random muting. But as said before, these results cannot be totally counted as correct, since there can be cells with the same ID and the same muting sequence. The user will count all those cells as detected, without being able to be sure if all of them have actually been received and without to be able to differentiate from which cells exactly the signals are coming from. This will translate in errors in the positioning.

To present the results then in a fair manner, cells with the same ID that transmit at the same time will not be counted as detected. That changes the results significantly. As it can be seen in figure 39, the random muting algorithm now performs significantly better compared to PCI muting and neighbor based muting. Given that in random muting the probability that two cells with the same ID will also have the same muting sequence is quite small, the number of detected nodes with no conflict is significantly higher. The simulated network for this thesis reuses several IDs which raises the number of the previously explained detection conflicts. Seems then than the problem of cell ID reuse is more important compared to having neighbors with the same frequency shift when it comes to the performance of muting patterns. Then, it is to be expected that a random muting algorithm will give better results, since it is not based in the cell ID.

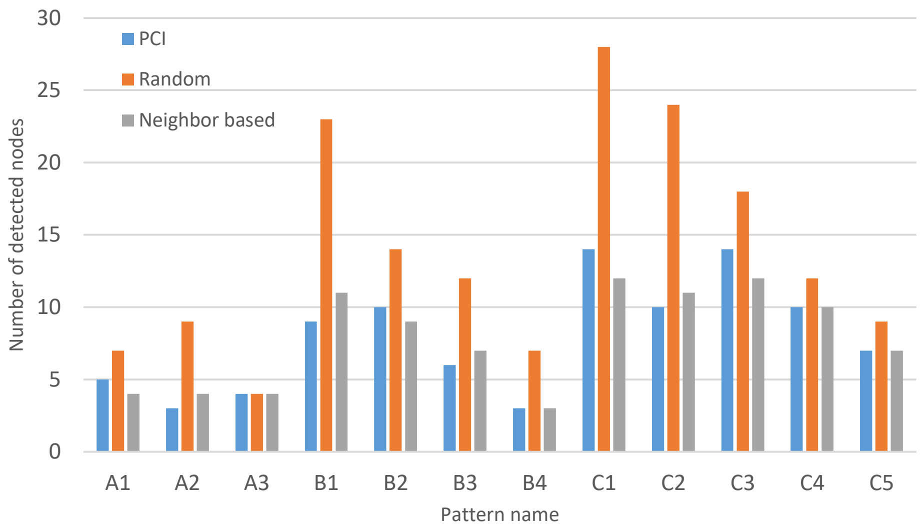


Figure 39. Comparison between different muting patterns, number of detected nodes

Pattern name	T_{REP} (Length)	Duty cycle	PCI muting	Random muting	Neighbor based muting	PCI muting hexagonal cell (ideal)
A1	4	0.25	400	600	300	1000
A2	4	0.5	200	800	300	1100
A3	4	0.75	300	300	300	500
B1	8	0.125	800	2200	1000	1900
B2	8	0.25	900	1300	800	1200
B3	8	0.5	500	1100	600	1400
B4	8	0.75	200	600	200	1100
C1	16	0.0625	1300	2700	1100	2300
C2	16	0.125	900	2300	1000	2400
C3	16	0.25	1300	1700	1100	1600
C4	16	0.5	900	1100	900	1700
C5	16	0.75	600	800	600	1400

Table 5. Percentage of increase on the cell detection compared to no muting

In table 5, the improvement that each muting pattern brings as a percentage of the number of cells detected with no muting is presented. Taking into account the results of PCI muting in a hexagonal network as the ideal muting, it can be seen that the random muting algorithm is the one that achieves the closest results to the ideal muting.

When comparing the results obtained for PCI muting with the ones obtained in the study done Srinivasan et al. [6] it can be seen that even though the percentage values are different, they do follow the same trend. Length 16 with duty cycles 0.0625, 0.125, 0.25 and 0.5, together with length 8 and duty cycles 0.125 and 0.25 achieve the highest results as far as number of detected nodes. In the results obtained in this thesis the different combinations present a higher increase in the number of detected nodes compared to the studies performed in the previously mentioned paper. A variation on the percentage of detected cells was to be expected, since even though the same area size and number of cells has been used for the network simulation, the methodology and network elements taken into account was different. The simulations environment developed for this thesis has into account more elements, such as the generation of the positioning signal itself, delay, different attenuation for each signal depending on the distance and actual correlation as a method of detection. The previously referred paper does only a study on the estimated power of the signal without generating the positioning signals, giving every signal the same initial power, the same attenuation and no delay.

In addition, the study by Srinivasan et al. [6] only tests combinations of T_{REP} and duty cycle of PCI based muting. In this thesis, the same study has also been performed for random muting and neighbor based muting. No studies have been found on these muting patterns to compare with.

When comparing the SINR achieved by the different muting patterns for different signals it can be seen that both PCI muting and neighbor based muting result on almost the same values for all the combinations of T_{REP} and duty cycle. The values of SINR are not consistent with the combinations of length 8 and duty cycle 0.125 and length 16 and duty cycle 0.0625 giving the highest SINR values for signal 1, while those same combinations give very low values for signal 2. The combinations of length 8 and duty cycle 0.25 and length 16 with duty cycle 0.125 and 0.25 give the best SINR results for signal 2. For both signals the maximum values for SINR are reached in patterns with length 16.

The SINR values for random muting for both signals are more consistent, being low and without much variation for patterns with length 4 and 8. The SINR value raises considerably for patterns with length 16 and duty cycle 0.0625, 0.125 and 0.25.

Giving the comparisons made for the number of detected nodes for each pattern, seems that the optimal choice for the network simulated in this thesis is to use a random muting pattern. The optimal combinations to use would be length 8 and duty cycle 0.125 and length 16 with duty cycle 0.0625 and 0.125.

Based on the results obtained for the values of the SINR the best patterns to use to achieve a high SINR for both signals would be PCI muting or neighbor based muting with length 16 and duty cycle 0.125 and random muting with length 16 and duty cycle 0.0625.

Having into account both the results for the number of detected nodes and the values for the SINR, a random muting pattern with length 16 and duty cycle 0.0625 seems to achieve the best results for the network simulated in this thesis.

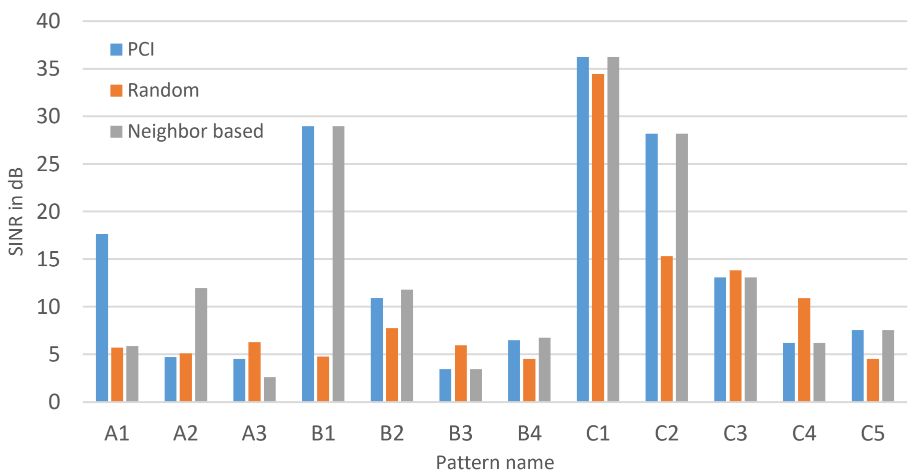


Figure 40. Comparison between different muting patterns, SINR values for signal 1

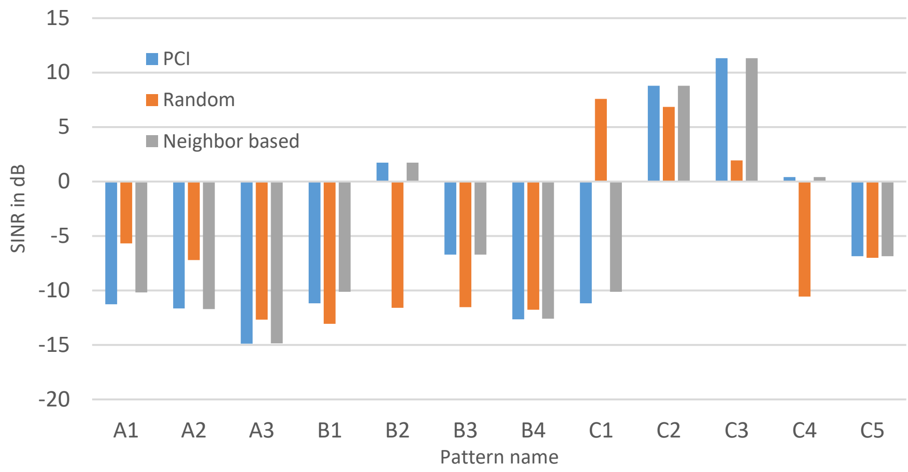


Figure 41. Comparison between different muting patterns, SINR values for signal 2

5.2 Future work

The simulation environment developed in this study can be further used to simulate any other possible muting patterns as well as different types of networks. It can serve as a foundation to add other elements, such as more users, other signals or alternative attenuation sources that can make the simulations even more detailed and accurate. One of the goals of the simulation environment built in this thesis was to keep it as high level and simple as possible. But it is feasible to build upon it, and make some of its elements more detailed by developing those in a lower level. It would be interesting to open this project to a wider group of engineers and get their input and possible modifications.

Due to privacy restrictions, it was not possible to compare the results of this simulations with real data obtained from the network. It would be interesting to have access to this type of data to compare it with the results obtained in this thesis. Furthermore, real data would be necessary to prove the validity of the results obtained in this study. The calculations performed in this thesis have been checked and done accordingly to the behavior of a network and follow the theory for signal processing. But there is only so much that can be validated without the access to real empirical data. It is advised then to undertake an empirical study in a deployed network of the number of detected nodes with the different muting patterns. This will help to validate the results obtained with the simulation environment and/or change some of the elements to make it as accurate as possible. But arranging this empirical study might be difficult due to the privacy policies in use at the moment.

In this study, one of the measurements for comparing the performance of muting patterns was the number of detected nodes. As explained before, the positioning server will send the user a list of 72 cells, normally neighbor cells, and this list will be sorted, so that the first nodes in that list are the ones the server is most interested to get measurements upon. Therefore, since the user does not know beforehand exactly which cells are in that list and how they are going to be sorted, all that can be done is to prepare the user to be able to detect as many of its neighbor nodes as possible. Taking into account this, the muting patterns that achieved a higher number of nodes were those whose length was 16. Using a muting pattern of length 16 can imply that even though the user is able to detect more nodes, it will take the positioning server longer to calculate the position of the user versus using a muting pattern with a length of 8. A study on the exact tradeoff between the number of detected nodes/muting pattern length and the time that it takes to calculate the position of the user could be performed. It is advised that this study should be done empirically rather than through simulations.

5.3 Conclusion

In this thesis, a simulation environment has been created with the goal of being able to simulate the behavior of a network during the positioning process and asses how this process is affected by different interference sources. The existent muting patterns (PCI muting and random muting) have been simulated. The effect that these patterns have in the overall interference of the network has been assessed by calculating the number of detected nodes as well as the SINR of the detected signals. It has been proven that the use of these patterns lowers the interference level of the network since more nodes where detected compared to the results obtained when not using any muting. A new pattern, based in the PCI muting pattern has been proposed. This new pattern takes into account the muting sequence of the neighbors of a cell, and tries to assign the cells a new muting pattern different from those of the neighbors. As the main goal of thesis was to assess the performance of the different muting patterns, they all have been compared to each other. For the particular network simulated, the random muting pattern was offering the best results when taking into account both the number of heard nodes as well as the values of the SINR.

5.3.1 Answering the research questions

In order to further summarize the study performed in this thesis, the research questions previously presented in section 1.3 are revisited. These questions have been answered throughout the report but in this section a more concise answer will be given for each one of them.

- **How does the interference between PRSs affects the precision of the positioning measurements?**
  Even though positioning signals have been design for low interference and therefore, will not suffer from interference from other signals, they can still interfere each other. What the level of this interference is could be seen when comparing the number of detected nodes in a network where no muting has been applied versus a network where some kind of muting was applied. Only 1 node was detected in a network where all the signals were being transmitted at the same time. When muting patterns where used, the lowest number of detected nodes was 3 and the highest number was 28. It can be concluded that the interference between positioning signals is still high and it can be greatly improved through the use of muting patterns.

  The positioning server calculates the position of the user. For that, it sends a list of the 72 closest neighbors to the user. The user's task is to detect and report measurements for as many of those cells as possible. The exact behavior of the server after receiving this information has not been found in any of the documents that could be accessed for this thesis. Therefore, since the only information the user has is that it needs to report as many of its neighbor nodes as possible, it is concluded that the higher the number of nodes detected the better.

- **How should the simulation environment be created? What is the minimum number of elements that should be included in the simulation environment?**
  The program used for the development of the simulation environment was Matlab. This choice was made mainly to increase the reusability of the environment created in this thesis. It also allowed the reuse of the network planning created in Matlab by S. Nyberg in [19]. The use of a simulation environment rather than a theoretical study increases also the reusability of the environment. Functions and elements can easily by changed to allow the simulation of other scenarios.

  This simulation environment was meant to be as simplistic as possible, but still include as much of the behavior of a network as it was needed. The elements included in the simulation and the reason behind this choice is explained in section 3.1. The simulation environment comprises a number of cells and one user. Each cell will transmit a PRS signal. The exact structure of this positioning signal needed to be generated. The signals would then be modulated to be able to be transmitted through a physical channel. The channel adds attenuation though one of the general attenuation models, in this case the Log Distance Path Loss Model. It also adds delay based on the distance. Lastly the signals are added to each other at the receiver where they are compared to the sent signals in order to determine which of those signals have been detected. A block diagram of all these elements can be found in Annex 1.

- **What different approaches of the muting pattern can be proposed?**
  There are two main approaches of the muting pattern. PCI muting is a straight forward approach that takes into account the ID of a cell to assign a muting sequence. If two positioning signals with the same frequency shift can interfere each other, then to lower the interference, those two signals should be assigned different muting patterns. But this approach is not as foolproof as it sounds. For some combinations of T_{REP} and duty cycle there might not be enough muting sequences to give each signal with the same frequency shift a different sequence. Also cell ID reuse is a common practice in deployed networks. Two cells with the same ID will produce the same positioning signal, and with PCI muting they will be assign the same muting sequence. The signals will be transmitted at the same time and the user will not be able to differentiate between them.

  Another of the already existent muting patterns is random muting. This pattern those not have into account any information about the cell when assigning a muting sequence. The assignment is done in a completely random manner. This solves almost completely the previously mention problem of cell ID reusing, since the probability that cells with the same ID are assigned the same muting sequence is quite low. Nevertheless, its performance is not as stable as the one obtained with PCI muting. The muting sequence assignment for each simulation for the same network will be different and therefore varying results can be expected.

  A new muting pattern created in this thesis has been called the neighbor based muting pattern. This pattern is based in the PCI muting patter but will take into account the muting sequences assigned to the neighbors of a cell and try to give the cell a muting sequence different from all of the neighbors' sequences. This aims to fix as much as possible the problem of cell ID reuse when using PCI muting. But this pattern might not be able to solve as many problems as intended. Firstly, same as with the use of PCI muting, with some combinations of T_{REP} and duty cycle there might not be enough number of muting sequences to give each neighbor a different one. Lastly, if several cells are reusing the same ID but they are not neighbors, the muting pattern will still not fix the positioning signal conflict.

- **Which approach creates less interference between PRSs?**
  The three muting patterns previously described have been simulated in the simulation environment created. The results have been compared both in the number of detected nodes and SINR of the detected signals. The overall results can be found in section 5.1.2. For the particular network simulated in this thesis, it could be extracted that neighbor nodes with the same frequency shift and same muting pattern where not the biggest problem. The existence of nodes with the same cell ID and same muting pattern increased the number of conflicts and represented a huge decrease in the number of detected nodes. Therefore, in this type of network, the random muting pattern seemed to be offering the best results both in the number of detected nodes and the SINR values achieved. Out of all the possible T_{REP} and duty cycle combinations of the random muting pattern, length 16 with duty cycle 0.0625 offered the best results.

5.3.2 The thesis in a wider context

The importance of positioning was outlined in the introduction chapter. Positioning is being used when an emergency phone call is placed so that the emergency services have almost immediate access to the position of the user. Knowing the position of the user allows the emergency services to get to the location of the user sooner, saving an amount of time that could be decisive to save the life of a person.

In addition, the E911 regulation places strict requirements on the accuracy of the positioning, not allowing to offer any services to those network operators that do not comply with these accuracy requirements.

The study done in this thesis shows a comparison between the different muting patterns based on the number of detected nodes and the SINR of the received signals. This can serve as a base for the network operators to know what performance they can expect from those muting patterns and help in their decision on which pattern to choose to achieve more accuracy. The study perform in this thesis can also serve as a guideline for an empirical study on the performance of the different muting patterns.

This study as well as any other progress done within positioning methods is very valuable in the actual market. Network operators need to invest in positioning and improve the positioning methods if they want to continue to offer their services. Even more important, having an accurate calculation of the positioning to give to the emergency services can make a huge difference when saving the life of a person.

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Annex

Annex 1 – Simulation environment block diagram

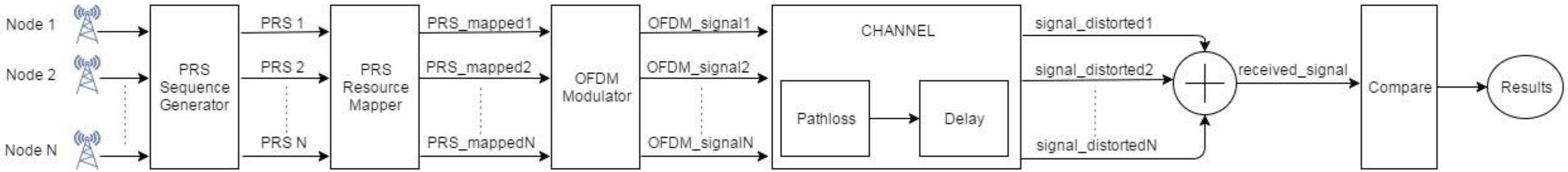

Figure 42. Simulation environment block diagram.