LUT School of Energy Systems

Bachelor's thesis, Electrical engineering

System Performance on Cellular Networks Supporting Industrial Applications

Teollisten sovellusten suorituskyky matkapuhelinverkossa

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ABSTRACT

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In this thesis the objective is to introduce the basics of IEC 61850 communication protocol and its messages, the Radio Access Network (RAN) slicing in wireless networks, and the metrics of the wireless networks to evaluate the performance of communication network. The RAN slicing approach is used to evaluate the IEC 61850 standard on 5th Generation (5G) cellular networks by simulation of four representative scenarios.

The simulation scenarios do have different client locations in relation to base stations. One scenario is related to the simulation with default settings, where clients are spread randomly in the base stations coverage area. The other three scenarios are for clients spread equally in the coverage area, clients located only in one base stations coverage area, and another in the center between the base stations coverage area. Each of the scenarios were simulated with base station distances of 100 meters and 200 meters.

The network performance was measured based on the spectral efficiency and the interference. Depending on the scenario, the spectral efficiency was mostly above the simulators reference values. The interference of the system was higher in the scenario where all the clients were in the coverage area of one base station. Distance between base stations did have effect on these key metrics, but there were no sign that distance would be proportional with these key metrics, specially in the performance of each individual RAN slicing.

TIIVISTELMÄ

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Tutkielman nimi	Teollisten sovellusten suorituskyky matkapuhelinverkossa
Akateeminen yksikkö	LUT School of Energy Systems
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Tämän tutkielman tavoitteena on esitellä IEC 61850 -standardin kommunikaatioprotokolla ja sen viestit, esitellä RAN-siivutus langattomissa verkoissa, sekä esitellä langattoman verkon suorituskyvyn mittareita, jotta voitaan tarkastella verkkoyhteyden suorituskykyä. RAN-siivutusta käytetään simuloitaessa neljää eri skenaariota IEC 61850 -standardista 5G-verkossa.

Simuloitavat skenaariot sisältävät erilaisia asiakaslaitteiden sijainteja suhteessa tukiasemiin. Ensimmäinen skenaario on simulaattorin vakioasetuksilla, jolloin asiakaslaitteet ovat jakautuneet satunnaisesti tukiasemien kantaman alle. Toisessa skenaariossa asiakaslaitteet ovat jakautuneet tasaisesti, kolmannessa ainoastaan yhden tukiaseman alaisuuteen ja neljännessä keskelle. Kaikki skenaariot simuloidaan 100 ja 200 metrin tukiasemien välisellä etäisyydellä.

Verkon suorituskykyä mitattiin spektrin hyötysuhteen ja häiriöiden voimakkuuden avulla. Spektrin hyötysuhde oli enimmäkseen parempi kuin simulaattorin referenssiarvo. Järjestelmän häiriöiden taso oli suurempi skenaariossa, jossa asiakaslaitteet olivat yhden tukiaseman keilassa. Tukiasemien välinen etäisyys vaikutti skenaariosta riippuen, mutta sillä ei voitu todeta olevan suoraa vaikutusta käytettyihin mittareihin, eikä varsinkaan yksittäisiin RAN-siivuihin.

Contents

Nomenclature

RAN	Radio Access Network
LAN	Local Area Network
GOOSE	Generic Object Oriented Substation Event
SMV	Sampled Measured Values
MMS	Manufacturing Messaging Specification
LTE	Long Term Evolution
5G	5th Generation
QoS	Quality of Service
DNP3	Distributed Network Protocol 3
SV	Sampled Values
ADSL	Asymmetric Digital Subscriber Line
VLAN	Virtual Local Area Network
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol / Internet Protocol
4G-LTE	4th Generation Long Term Evolution network
TLS	Transport Layer Security
IED	Intelligent Electronic Device
MU	Measurement Unit
eMBB	enchanted mobile broadband
mMTC	massive machine type communication
URLLC	ultra-reliable low-latency communication
IoT	Internet of Things
VPN	virtual private network

1 Introduction

The objective of this bachelors thesis is to evaluate wireless communication networks supporting an industrial protocol used in power systems. This protocol is defined in the standard IEC 61850.

The traditional usage of IEC 61850 is on Ethernet wired connectivity, usually using fiber optics or copper wire communication.

Based on the network slicing concept defined in 5G, a variety of services with a variety of requirements can be enabled by isolated logical resources, sharing the same physical resources as indicated in Vo et al. (2018). When the network slicing concept is applied on the physical layer of the communication network, it has the name of RAN slicing. In this study, we use a wireless networks with capabilities to optimize the resource allocation of the RAN slicing framework.

RAN slicing aims to guarantee isolation between slices and optimize an efficient usage of available radio network resources.

1.1 Background

Kunz et al. (2017) defines a methodology realising the real-time requirement of IEC 61850. They introduce quite well the messages defined in the standard and also give some examples of usage of the messages. The research only focuses on Generic Object Oriented Substation Event (GOOSE) and Sampled Measured Values (SMV) message types, which do have a real-time requirement. They also mention the Manufacturing Messaging Specification (MMS) message type in order to find out that it does not have a real-time requirement.

Leal et al. (2018) did research on Quality of Service (QoS) in substation networks where IEC 61850 messages are used. QoS policies are needed also in wired connections to make sure that the network fulfills the requirements of the messages. The research recommends values for network throughput in different protocols and priorities, which are really useful for our case. Unfortunately the research focuses only on wired connections.

O. Villalta et al. (2018) focuses research on comparing Distributed Network Protocol 3 (DNP3) and Sampled Values (SV). The research examines sampled values and how different metrics have an effect on the quality of service. In our case this research is not that useful because it does not contain any numeric data. However the description of the effect of the metrics on quality helps to sort out which metrics are more important than others in the view of SV.

Saraiva et al. (2019) compared Asymmetric Digital Subscriber Line (ADSL), optical fibre and 4th Generation Long Term Evolution network (4G-LTE) networks with the IEC 61850 messages. Usually these IEC 61850 messages are transmitted through wired connections. The research cases focuses on the 4G-LTE connections. They introduce the messages and also give some example applications for these messages. The weakness of wireless networks is proven to be propensity to errors, which should get better in 5G networks. The research work supports the need to do more research on 5G networks.

Kalalas et al. (2016) is another research that focuses in using Long Term Evolution (LTE) networks with IEC 61850 messages. This work focus on grid automation, which means message types GOOSE and MMS. The LTE network did not fulfill the requirements of IEC 61850 messages without improvements on scheduler. The research gives a motivation to do research on 5G networks to find out if they are good enough for the IEC 61850 messages.

1.2 Objectives

The goals of this bachelor thesis are summarized in the following list.

- to define representative scenarios in power system industry that use IEC 61850 protocol,
- evaluate the performance of the wireless network on scenarios that use IEC 61850,
- compare the network system performance with requirements defined by each IEC 61850 message types.

1.3 Methods

The main methods in this research are based on a literature review and simulations. The literature review is used in providing a basic knowledge of IEC 61850 messages and their requirements for the network. Simulations are used to evaluate if the wireless network performance is aligned with the IEC 61850 requirements. The methods are shown in figure 1.

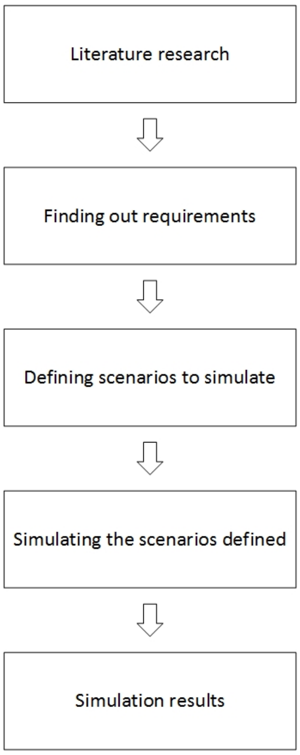

Figure 1: Thesis methodology.

The simulator used in this research is python based simulator and TensorFlow framework, which focuses on the application reinforcement learning on RAN slicing.

1.4 Structure

This work is divided in 6 sections. The First section contains introduction and methods used in this study. The Second section introduces the IEC 61850 messages model and the messages description. The Third section introduces the metrics used to measure wireless networks and the requirements of the IEC 61850 messages. The Fourth section is about wireless network and describes the network model used. In the Fifth section is defined three specific scenarios to be simulated. The last section discusses the results obtained by simulation.

2 IEC 61850 messages

There are three different types of messages used in IEC 61850 communication. These messages are used in different cases and thereby do also have different requirements (Kunz et al. (2017)). The messages are transferred via Ethernet connection (Saraiva et al. (2019)). The devices that are using these messages are normally used in a Local Area Network (LAN) or Virtual Local Area Network (VLAN), which means that they are separated from the internet to their own network.

These messages are used in different IEC 61850 communication levels, which are process, bay and station level (Altaher (2018)). There are typically the measuring devices in the process level, which do measure i.e. voltage or current. In the bay level there are remote protection and Intelligent Electronic Devices (IEDs). The station level is for communications from the station to others and also for supervisory.

The reason why this IEC 61850 communication protocol is defined comes from the need to have a plug-and-play connection between devices (Altaher (2018)). In the market, there are many different manufacturers that produce devices used in substation, and to make all these different devices to work together, there must be a standard that defines the communication between them.

2.1 Data Model

To understand more about the messages it's important to get in touch with the IEC 61850 data model. The reason why data model has been implemented is to make sure that devices from different manufactures are capable to work together.

The data model contains different layers. It bases on the physical device, which has a network address. The physical device can be for example an IED. On the physical device, there are logical device which has logical nodes. The control, monitoring and measuring is done inside the logical device. Each logical node has their own Measurement Unit (MU). (Saraiva et al. (2019)). These MUs have analog inputs for voltage and current, one input for time synchronization, and they output SMV by their ethernet connection (Altaher (2018)). The data model is presented in figure 2.

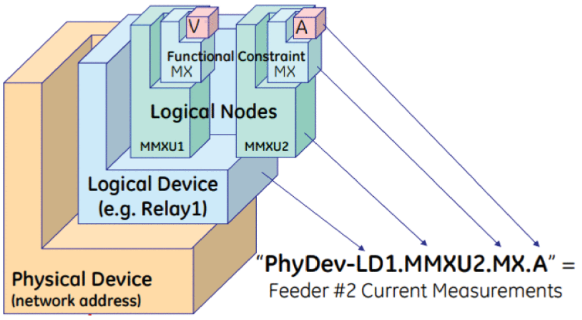

Figure 2: IEC 61850 Data Model (Saraiva et al. (2019))

2.2 GOOSE

Kunz et al. (2017) introduces GOOSE as a high priority message that requires real-time connection and it is used in asynchronous, unsolicited and heartbeat messages. The research also lists some more characteristics of GOOSE: The protocol is enclosed in the Ethernet layer, message type is multicast and the message uses retransmission. The definition is quite short, but it contains the main parts of GOOSE.

Saraiva et al. (2019) defines GOOSE as a Peer-to-Peer connection which is used to transfer common data. This research's definition for GOOSE supports the definition found in Kunz et al. (2017), but is much more simplified.

Leal et al. (2018) found out from the IEC 61850-9-2 that the function of the GOOSE is to exchange event data, like indications, alarms and commands, between substations in their network. The research also defines some characteristics of GOOSE that helps to define the requirements, like messages size and maximum transfer time. This research focuses more on messages requirements than defining the GOOSE message type, which is not helping in finding out what GOOSE is, but it helps later when finding out the requirements.

Another interesting point found in Leal et al. (2018) is that GOOSE has two kinds of messages send. One is heartbeat message which is sent periodically and another is a burst sent by trigger, for example when a failure is detected.

Rai et al. (2021) states that GOOSE is used in communication between IEDs and also on communication from the IEDs to the network operator. The usage of GOOSE is presented in figure 3. GOOSE communication method is publisher to subscribers, which is quite close to former defined multicast (Bhattacharjee & Jamil (2019)). The main difference between multicast and publisher/subscriber methods is that in publisher/subscriber method only the subscribers receives the information that publisher sent.

ABB (2017) mentions that GOOSE is directly on the Ethernet layer because of its need of real-time communication. By extending the research by another (ABB (2016)) which introduces that GOOSE messages are delivered only for the IEDs that have subscribed the data. The latter research also confirms that GOOSE uses publisher-subscriber communication method.

GOOSE's publisher/subscriber communication method uses multicast without acknowledgement in time-critical protection functions (Altaher (2018)). This type of GOOSE is used between bay-level devices.

The data values that GOOSE contains, is grouped into data sets (Altaher (2018)). This data grouping helps other devices to analyze the data and to make decision.

To sum up what kind of message GOOSE is the main characteristics are listed:

- A high priority message with real-time requirements.
- A publisher-subscriber message type transferred in Ethernet layer.
- Asynchronous, heartbeat and unsolicited message.
- Used in transferring common data, like events, commands, alarms and indications.

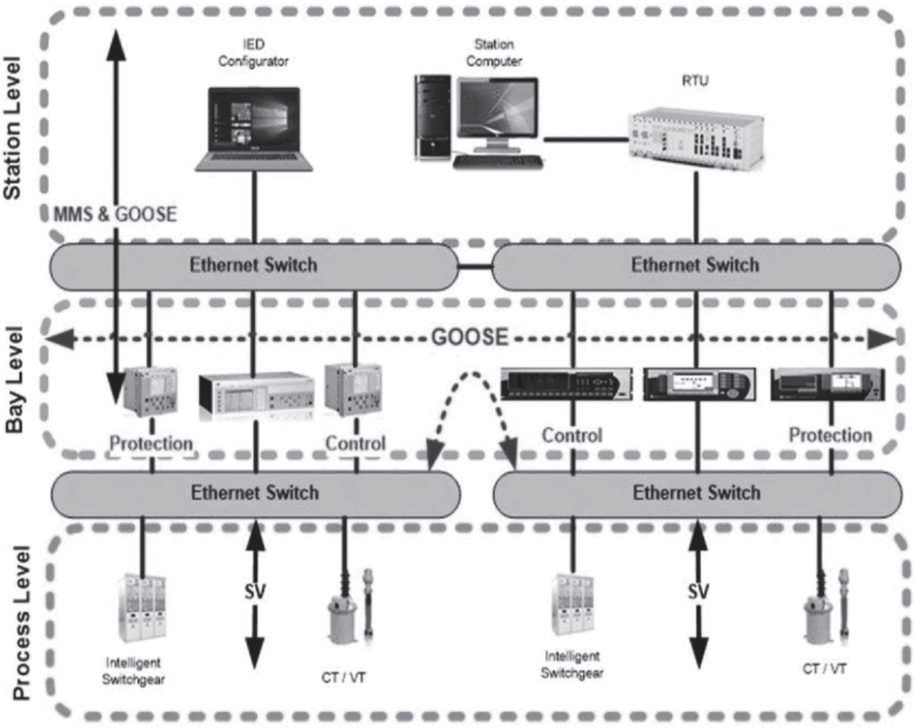

Figure 3: IEC 61850 Substation communication model (Rai et al. (2021))

2.3 SMV

O. Villalta et al. (2018) defines SMV as message type that is used to transfer a signal with high sampling rate, which allows detailed system analysis. The research gives the use for the SV, but is not introducing the message type itself.

Kunz et al. (2017) introduces SMV as a data transferring message that has real-time requirements. The research knows that the message type could be used as a part with signal processing and also describes the messages transfer process. The definition of SMV is really short and focuses mostly on usage of the message.

Leal et al. (2018) mentioned that SMV could also be used in metering accuracy and quality. In the research analog values such as voltage and current were given as examples of sampled raw data. The study focuses mostly on the requirements of SMV, but also describes the usage of message type quite well.

Saraiva et al. (2019) tells that SMV uses Client-Server model and is used for transferring sampled raw data, which is measured in substation, cyclic and fast. This research introduces not only the usage of the SMV but also the message type itself.

The use case of SMV described in Rai et al. (2021) is the communication between IEDs and MUs. The usage of SMV is presented in figure 3

ABB (2017) mentions that SMV is directly on the Ethernet layer because of its need of real-time communication. ABB (2020) presents the real-time communication as a communication between one publisher and a number of subscribers. This means that SMV uses also a publisher-subscriber model instead of client-server model that was former found by Saraiva et al. (2019).

SMV is used for transferring data from process level to the bay level devices (Altaher (2018)). This research helps to understand the communication between devices a bit more with different levels for different types of devices.

The SMV is divided in three different classes of performance, which does depend on the sampling rate. The sampling rates are 480, 960 and 1920 samples per second. All of these messages do require accuracy of one microsecond. The accuracy is important because of encapsulated timestamp data that requires precise synchronization. (Altaher (2018)) These different performance classes do affect the requirements for the network. It's also important to know what defines the performance class of the message.

To sum up SMV:

- Real-time requirements
- Client-Server model
- Used for transferring sampled raw data, such as voltage and current

2.4 MMS

Kunz et al. (2017) defines MMS as a non real-time message type that is used in remote configuration and supervisory communication. The research is not focusing on MMS because it's not having a real-time requirements.

Leal et al. (2018) gives as use for MMS transmitting management related information from the substation to the user interface system. The study defines also requirements for the MMS message protocol for different use cases such as automatic interactions, operator commands, both events and alarms and file and log transfer. The research focuses more on requirements of the messages than the message type itself.

Ustun & Hussain (2020) goes deeper in MMS security, but also introduces the implementation of MMS. The MMS is an application layer protocol, that uses Transmission Control Protocol (TCP) protocol over Ethernet. By the less strict requirements for the latency, MMS can use Transport Layer Security (TLS) security mechanism which is too slow for GOOSE and SMV.

According to the Rai et al. (2021) MMS is used only in communication between IEDs and network operator. The usage of MMS is shown in figure 3.

ABB (2017) confirms that MMS uses a client-server model on Transmission Control Protocol / Internet Protocol (TCP/IP) connection.

To sum up MMS:

- Does not have a real-time requirement.
- MMS is an application layer protocol that uses TCP.
- Is used transferring automatic interactions, operator commands (such as remote configuration), events, alarms, files and logs.

3 IEC 61850 Requirements

Recommendations for the GOOSE and SMV communication redundancy are defined in the IEC 61850s second edition (Altaher (2018)). These recommendations can be applied into requirements for the network.

3.1 Metrics

The wireless network do have different kinds of metrics. These metrics can be used to define the performance of the network and/or to compare the networks. These metrics are throughput, latency, packet loss ratio, availability and packet delivery variation (Polunin (2018)). The performance of network does not only depend on the network itself, but also the users affect on the networks performance.

3.1.1 Throughput

Polunin (2018) defined throughput as amount of bits delivered successfully in a time period. This definition is easy to understand by thinking about units, for example bits per second. Throughput describes the capacity of the connection. Throughput is typically Megabits/seconds.

3.1.2 Latency

Latency is a value that describes the time period that one packet takes to travel from the sending device to the receiving device (Polunin (2018)). Latency is typically measured in milliseconds.

According to the ABB (2017), the latency contains not only the delay of physical connection, but also the package encoding and decoding.

3.1.3 Packet loss ratio

As the name states, this measures which percentage of packets got lost during the transfer. This could be calculated by dividing number of lost packets by number of packets sent. Polunin (2018) examined reliability instead of packet loss ratio. Reliability means percentage of packages successfully delivered. It could be calculated by dividing number of successfully delivered packets by number of packets sent.

3.1.4 Availability

Polunin (2018) defined availability as a probability that network is working in a point of time. As availability is an probability, it’s measured in percents.

3.1.5 Packet delivery variation

Packet delivery variation is kind a part of latency, because it tells the amount of variation in latency (Polunin (2018)). Packet delivery variation only counts successfully delivered packages and has a time period when measured. In worst case scenario, the

Protocol	Priority	Latency class (ms)	Throughput (Mbps)
GOOSE	High	TT6 - 3	3
GOOSE	High	TT5 - 10	0.02
GOOSE	High	TT4 - 20	0.02
SV	High	TT5 - 10	6
SV	High	TT5 - 10	12
MMS	Medium - Low	TT3 - 100	0.016
MMS	Medium - Low	TT2 - 500	0.0016
MMS	Medium - Low	TT1 - 1000	0.032
MMS	Low	TT0 - > 1000	1

Table 1: Requirements of IEC 61850 messages in terms latency and throughput Leal et al. (2018)

packet delivery variation could cause package reordering, if packet sent later than another is received earlier.

3.2 Requirements

The latency and throughput requirements of the messages are collected in the table 1. The latency is defined in IEC 61850, and throughput is calculated by making an estimation of packet size and amount of packets sent in a small period of time (Leal et al. (2018)). There are different values for throughput required with in the same IEC 61850 message type because of different use cases. For example GOOSE has two different values for required throughput, one for routine messages and another for rapid state change messaging.

The other metrics that are examined are packet loss ratio, availability and packet delivery variation. These are not that easy to be presented in a numeric form.

To consider on packet loss ratio in SMV, it reveal to be proportional as error in measured raw data (O. Villalta et al. (2018)). The amount of error affects directly on data, so the acceptable amount of packet loss depends on the application.

In GOOSE packet loss ratio has not that kind of effect, because it does a lot of re-transmission (Saraiva et al. (2019)). The same is also found by Leal et al. (2018), where this re-transmission is mentioned as a burst.

In MMS the effect of packet loss ratio has not a very big effect on data transferred, because of the usage of TCP/IP (Leal et al. (2018)). TCP does verify sent data and does re-transmission on failure (Farah et al. (2018)).

Availability has similar effect with all of these messages, no data can be sent when network is not available.

Packet delivery variation does have effect on latency and thereby the sum of packet delivery variation and latency should not be more than messages latency requirement. Likewise packet delivery variation should not be more than time gap between packets sent to avoid package reordering.

The most important requirements of these messages are the latency and throughput, because they could be defined as numerical values. The simulation should first focus on the messages with highest latency and throughput requirement, because the messages with lower requirement also pass the comparison if the higher ones passes the comparison.

4 Wireless networks

There are different technologies in wireless networks, but in this thesis the focus is on the 5G cellular networks. The reason to focus on 5G networks is the capability to RAN slicing, which is quite new technology and needs more research.

In this section the focus is on different types of services on 5G networks and getting to know RAN slicing approach, which relates tightly on 5G networks. In the first subsection the focus is on the 5G networks mobile services. In the seconds subsection the focus is on RAN slicing.

4.1 Mobile services

There are different types of services that 5G networks can support. The mobile services can be divided in three different types: enchanted mobile broadband (eMBB), massive machine type communication (mMTC) and ultra-reliable low-latency communication (URLLC) (Elayoubi et al. (2019)). All different devices and use cases do not count right into one of these services, they can also be in between of these services. The service types are shown in figure 4.

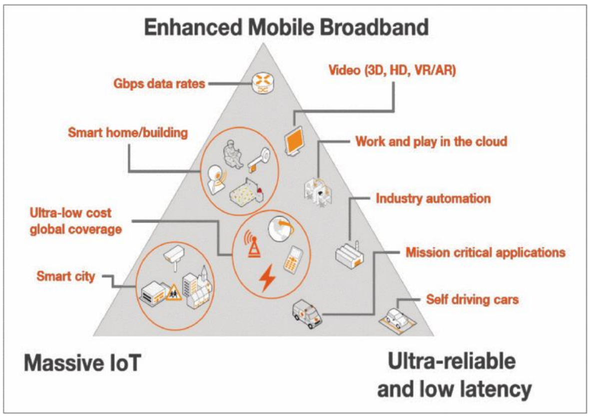

Figure 4: Mobile services and the use cases of them (Elayoubi et al. (2019)).

4.1.1 eMBB

eMBB is the only service that has been supported by the earlier network generations (Elayoubi et al. (2019)). It is used for normal customer devices like mobile phones, computers and so on. This service prioritizes on the throughput of the network to satisfy the needs of end users.

4.1.2 mMTC

When comparing to the earlier network generations, the mMTC is a new service in 5G networks. mMTC is used in Internet of Things (IoT) communications and prioritizes on capability to serve a huge amount of clients. (Elayoubi et al. (2019)).

4.1.3 URLLC

URLLC is a new service in 5G networks as well as mMTC. URLLC is used in many different cases where ultra reliable and very low latency connection is required (Elayoubi et al. (2019)). For example URLLC can be used with self driving cars and other time critical applications.

4.2 RAN slicing

The RAN slicing is a solution to separate the clients in different groups by their needs. The RAN slicing separates the hardware and software resources in different slices to serve all the clients by taking care of their requirements. For example the clients that can be categorized in the group URLLC are given the best possible latency.

There is no limit for the amount of slices, but when increasing the number of slices the amount of resources per slice decreases. There are different ways to categorize the services and decide the amount of slices (Elayoubi et al. (2019)). The amount of slices can be three, which is the amount of different types of mobile services that 5G supports. Usually there are a lot more slices, one for each use case. For example IEC 61850 messages could have three slices, one for each type of message.

Amount of shared resources can also be adjusted with RAN slicing. The resource sharing weakens the isolation but optimizes the resource usage and performance (Elayoubi et al. (2019)). The resource sharing options are shown in figure 5.

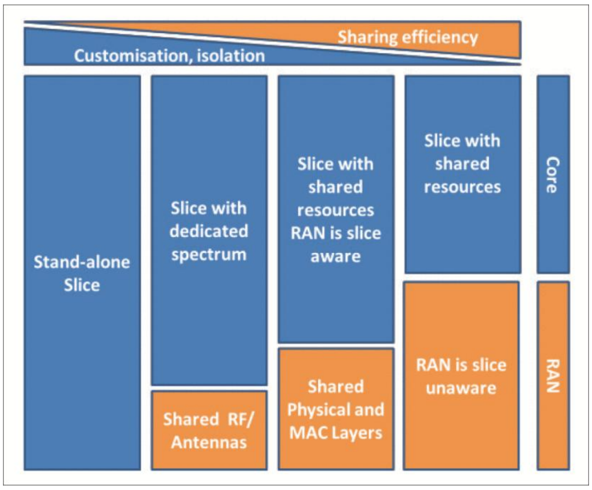

Figure 5: RAN slicing possibilities (Elayoubi et al. (2019)).

4.2.1 RAN slicing with IEC 61850 messages

In this thesis there are given one slice for each IEC 61850 message type, because the messages do have different requirements. Also in real use case these message type would have their own slices, because of number of clients and the need to be isolated from the other communication in the network. The need for isolation comes from the standard IEC 61850, where these messages are meant to be used inside local network or virtual private network (VPN) (Saraiva et al. (2019)).

In this case the RAN slicing helps to achieve the requirements of these IEC 61850 messages. The most useful feature of RAN slicing with IEC 61850 messages is to prioritize the messages that are having real time requirements by giving them the lowest latency possible.

5 Simulation Scenarios

In these different scenarios the variation comes from users location and density of users. All these simulations are ran with parameters that are summarized in the following list.

- Number of users is 12,
- Users do not move,
- Number of base stations is three (3),
- Number of messages is three (3),
- Radius of base station is 100 or 200 meters,
- Number of iterations or samples is 30000,
- Number of iterations per scenario is 10000, so there is three sub scenarios in one scenario.

These parameters are an estimation of amount of IEDs in the area that base stations coverage. These IEDs are stationary, so simulators mobility parameters are set for no movement. The number of messages comes from the standard, and the messages are GOOSE, SMV and MMS. There are two values for the radius of base station to find out if it has affect on the performance. All the scenarios following are simulated with the radius of the base station of 100 and 200 meters.

5.1 First scenario - random

In the first scenario users are located randomly in the area. This is the default setting of the simulator, and user locations are set randomly for each of the sub scenarios.

This scenario presents the power system distribution network with multiple small independent transformers.

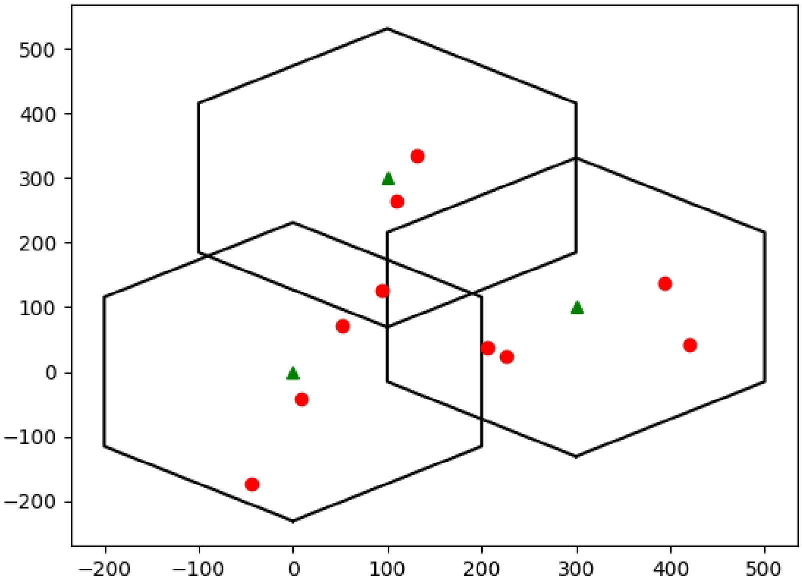

Figure 6: Users located randomly, base stations are 200 meters from each other.

5.2 Second scenario - one

In the second scenario the most of the users are located randomly in the area of one of these base stations. This scenario tests the performance of base station when it needs to serve all the clients.

This scenario presents a switch yard with multiple devices located in a relatively small area.

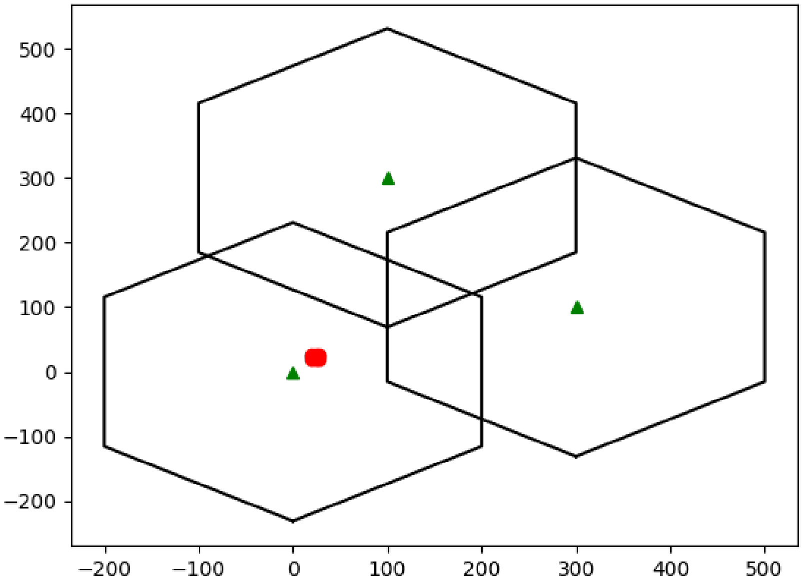

Figure 7: All users are located in the area of one base station

5.3 Third scenario - center

In this scenario the users location focuses in the border between base stations. This scenario is to test how the network works when there are multiple base stations available in the same area.

As well as the seconds scenario, this scenario also presents a switch yard with multiple devices located in a relatively small area.

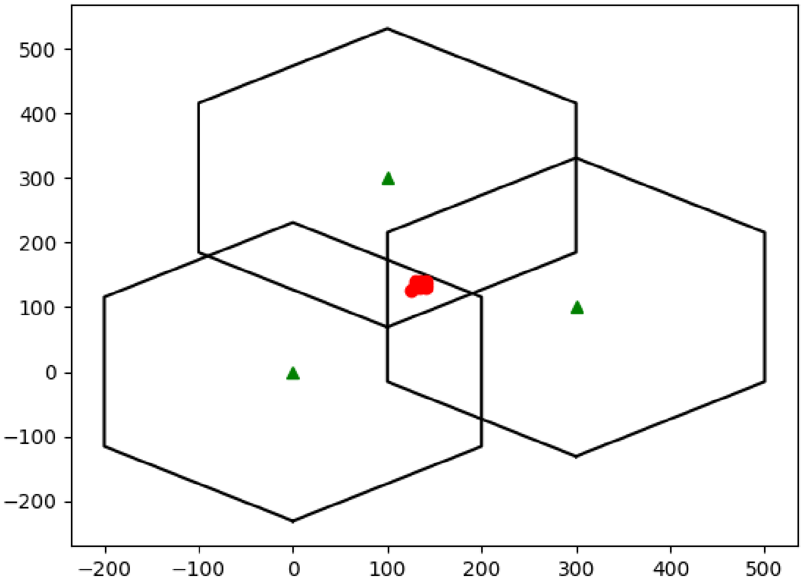

Figure 8: All users are located in the middle of the tree base stations.

5.4 Fourth scenario - equal

In this scenario the users are spread equally in the area of these base stations. The fourth scenario differs from the first one by user location definition by hand instead of randomly generated user locations.

As well as the first scenario, this scenario also presents the power system distribution network with multiple small independent transformers.

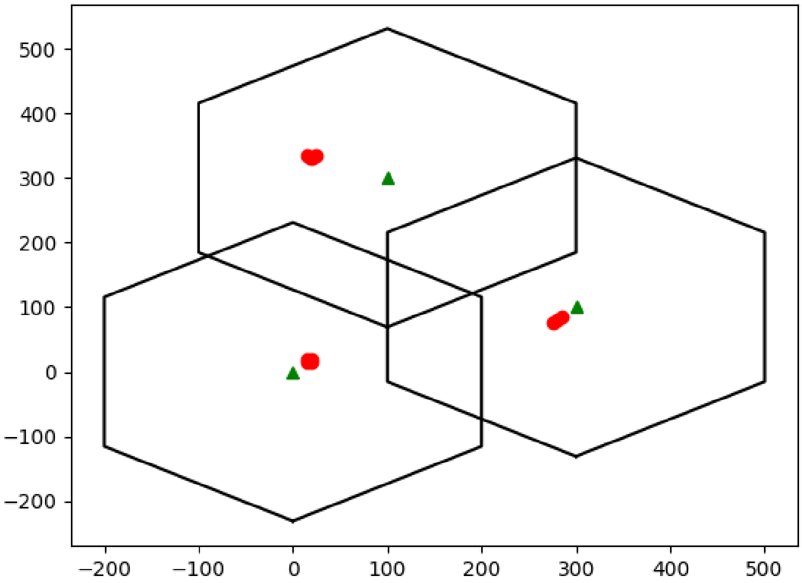

Figure 9: The users are spread equally in the area of these base stations

6 Results

6.1 Simulations

The simulation results are shown as spectral efficiency and individual slices. In the results there are comparison between base station distances and comparison between different scenarios with the same base station distance.

6.1.1 First scenario - random

The first scenario is about random user location. The spectral efficiency of the first scenario is shown in figure 10. The figure shows that spectral efficiency with base station distance of 200 meters is a bit higher in the first third of the iterations when comparing it to the distance of 100 meters. After the first third the situation turns around and base station distance of 100 meters has a bit higher spectral efficiency.

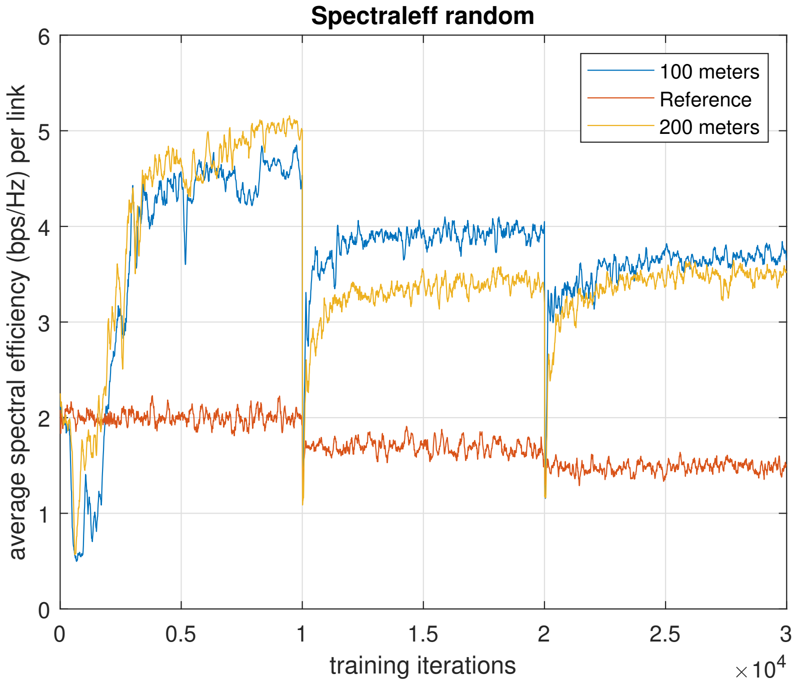

Figure 10: Spectral efficiency with random user location comparing base station distances between 100 and 200 meters

The spectral efficiency consist of the slices. All three slices are shown independently in different figures.

The slice number 1 is shown in the figure 11. In the slice number 1 the spectral efficiency is higher with base station distance of 100 meters in the first two thirds. In the last third of the spectral efficiency the efficiency with base station distance of 200 meters is higher.

Figure 11: Slice 1 with random user location comparing base station distances between 100 and 200 meters

The slice number 2 is shown in the figure 12. In this slice the spectral efficiency is quite same in the first third, but after that the scenario with base station distance of 100 meters has a bit higher spectral efficiency.

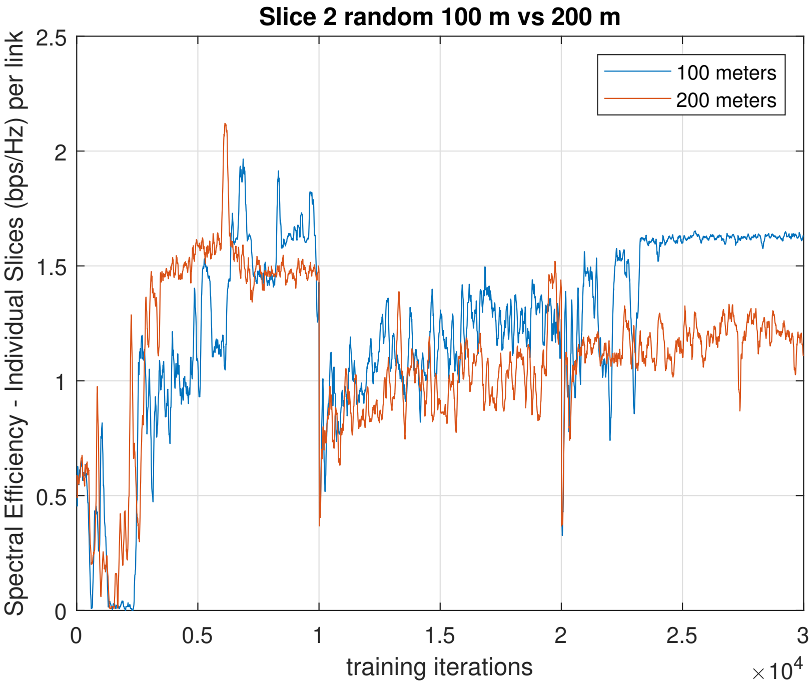

Figure 12: Slice 2 with random user location comparing base station distances between 100 and 200 meters

The slice number 3 is shown in figure 13 In this slice the spectral efficiency is higher in the scenario where distance of base stations is 200 meters in the first third. In the last two thirds the spectral efficiency is quite equal.

Figure 13: Slice 3 with random user location comparing base station distances between 100 and 200 meters

The average interference of the system in this scenario is shown in figure 14. In the first two thirds the interference stays in the level of -120 dBm to -180 dBm with both scenarios. In the last third the interference rises up to -60 dBm with base station distance of 200 meters. The interference with base station distance of 100 meters stays in the same level as before.

Figure 14: Interference with random user location comparing base station distances between 100 and 200 meters

6.1.2 Second scenario - one

There are all of the users located in the area of one base station in the scenario number 2.

The spectral efficiency of this scenario is shown in figure 15. The scenario with 100 meter distance between base station has significantly higher efficiency compared to the scenario with 200 meter distance. The efficiency with distance of 200 meters is lower when compared to reference value, when 100 meter has significantly higher efficiency compared to reference value.

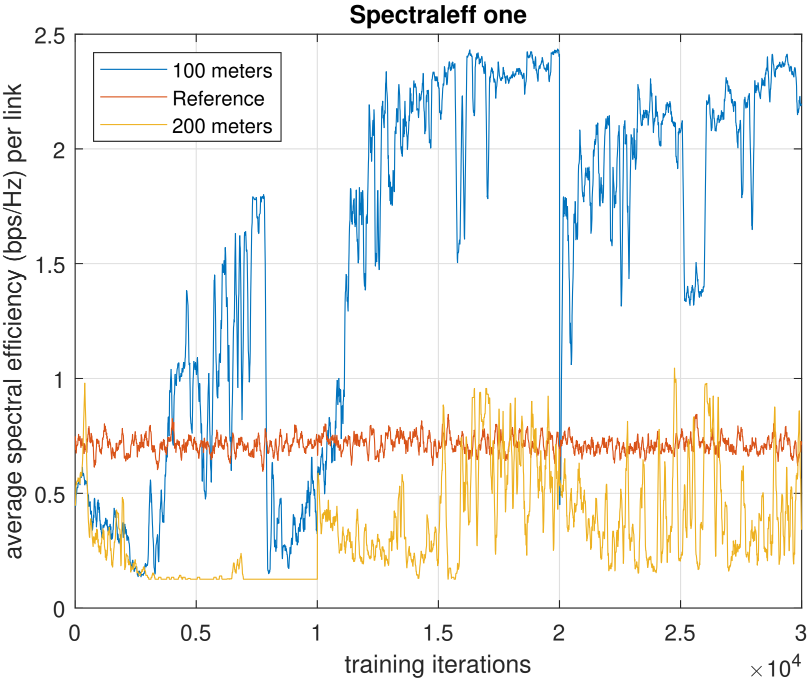

Figure 15: Spectral efficiency with users located in the area of one base station comparing base station distances between 100 and 200 meters

The slice number 1 is shown in figure 16. The efficiency of scenario with distance of 100 meters is significantly higher compared to scenario with distance of 200 meters. The scenario with distance of 200 meters has efficiency of 0 on iteration rounds from 5000 to 10000 and from 16000 to 20000.

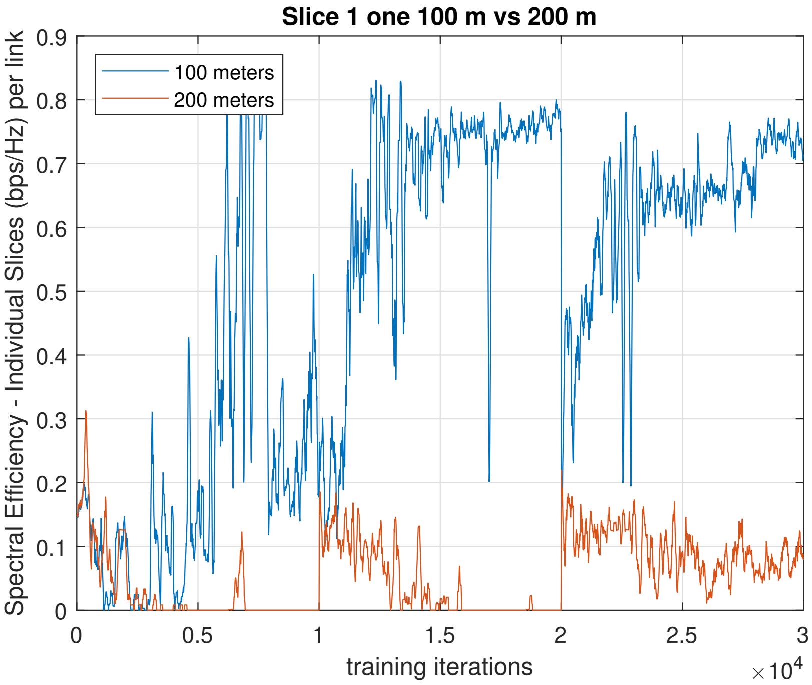

Figure 16: Slice 1 with users located in the area of one base station comparing base station distances between 100 and 200 meters

The slice number 2 is shown in figure 17 The efficiency of this scenario is more equal between distances. In the first half the scenario with 100 meter distance is significantly higher compared to 200 meter distance. Only exception on this is at iteration rounds between 8000 and 10000. In the seconds half of this figure can be noticed that efficiency is higher with 200 meter distance compared to the first half.

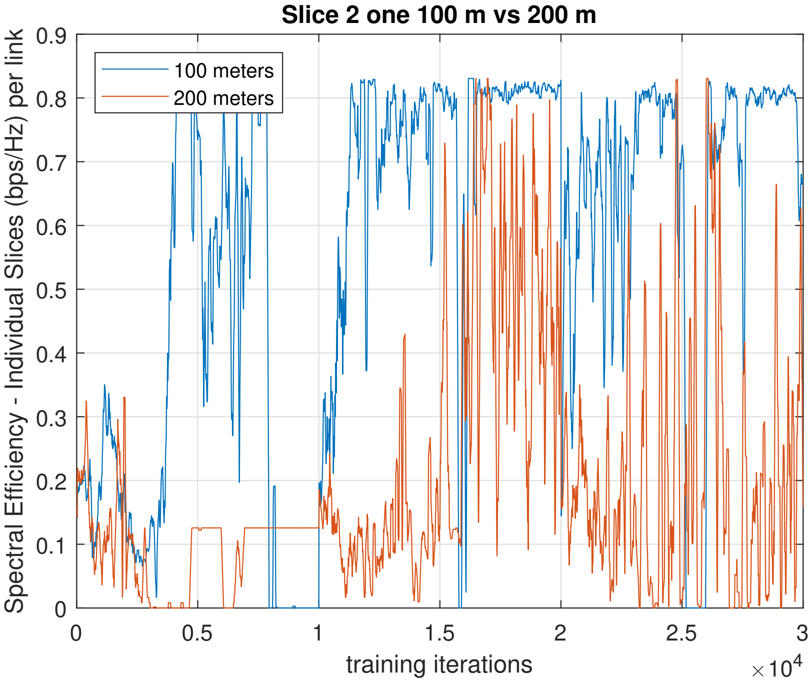

Figure 17: Slice 2 with users located in the area of one base station comparing base station distances between 100 and 200 meters

The slice number 3 is shown in figure 18 The efficiency of the scenarios is on the same level in the first third. The efficiency rises for the 100 meter scenario for the last two thirds of the training iterations. Meanwhile the efficiency of the 200 meter scenario stays on the same level for the whole simulation.

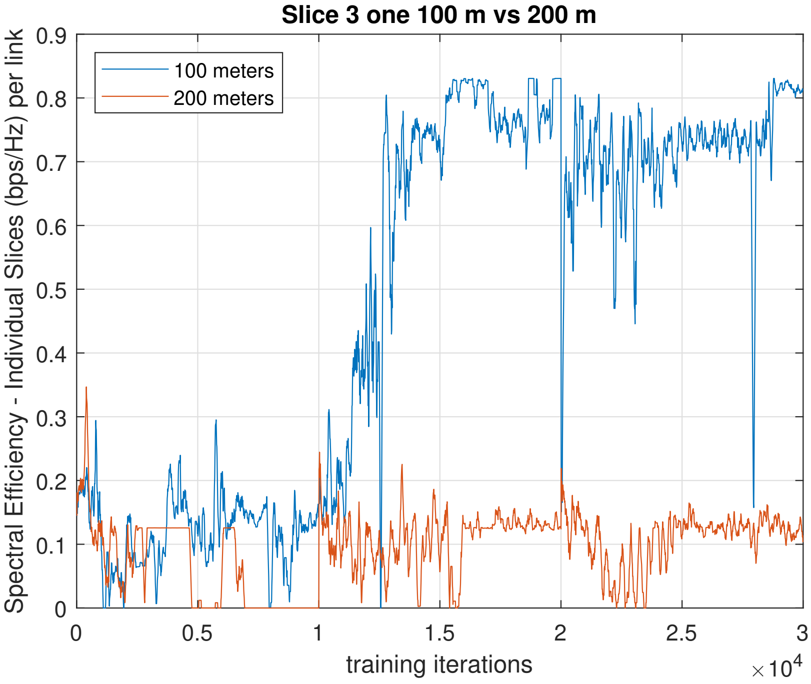

Figure 18: Slice 3 with users located in the area of one base station comparing base station distances between 100 and 200 meters

The interference of this scenario is shown in figure 19. The interference level of 200 meter distance starts from level of -40 dBm and decreases to the level of -50 dBm when going through the simulation. The interference level of 100 meter distance starts from -100 dBm, increases to -80 dBm and after that decreases slowly to the level of -120 dBm The interference of 100 meter distance is about 60 dBm lower when compared to scenario of 200 meter distance.

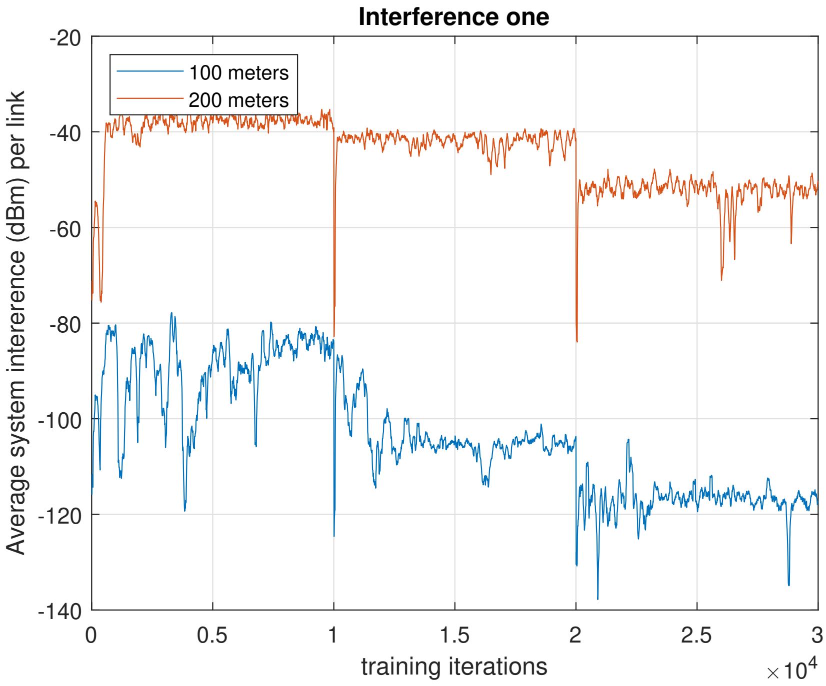

Figure 19: Interference with users located in the area of one base station comparing base station distances between 100 and 200 meters

6.1.3 Third scenario - center

In the third scenario there are all the users located in the middle of the base stations.

The spectral efficiency of this scenario is shown in figure 20. The efficiencies of the scenarios differ from each other in the last third of the iterations, when scenario with 200 meter distance is higher compared to the scenario of 100 meter distance. Both scenarios starts at the same level as reference, got lower than reference value, but rises to higher after a while. There is also a big drop in efficiency around the iteration number 20000. The 200 meter scenario rises after the drop to the same level it was before, but 100 meter scenario does not.

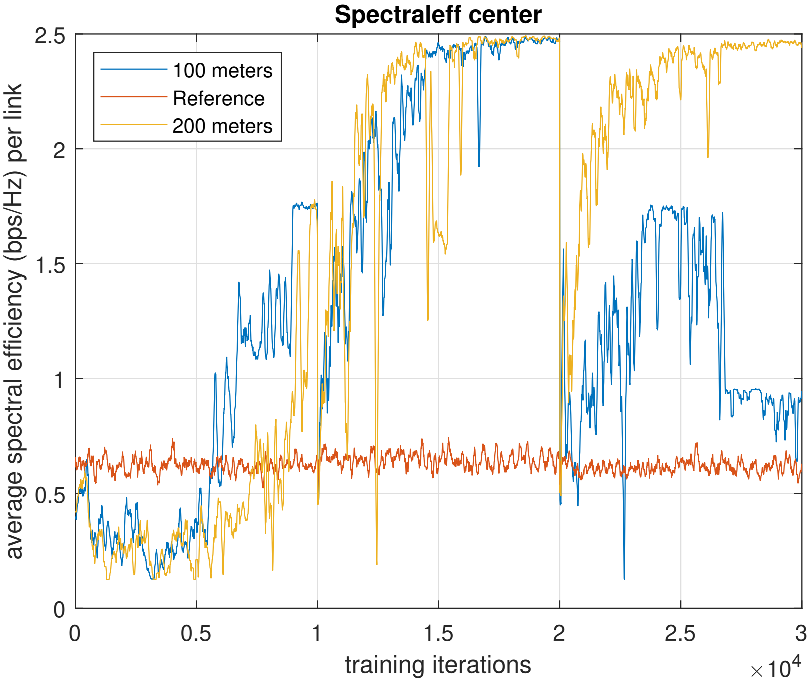

Figure 20: Spectral efficiency with users located in the center of the base stations comparing base station distances between 100 and 200 meters

The slice number 1 is shown in figure 21. In the beginning the scenario with 100 meter distance rises a bit faster compared to the scenario with 200 meter distance. In the last third the scenario with 200 meter distance is significantly higher compared to the scenario with 100 meter distance.

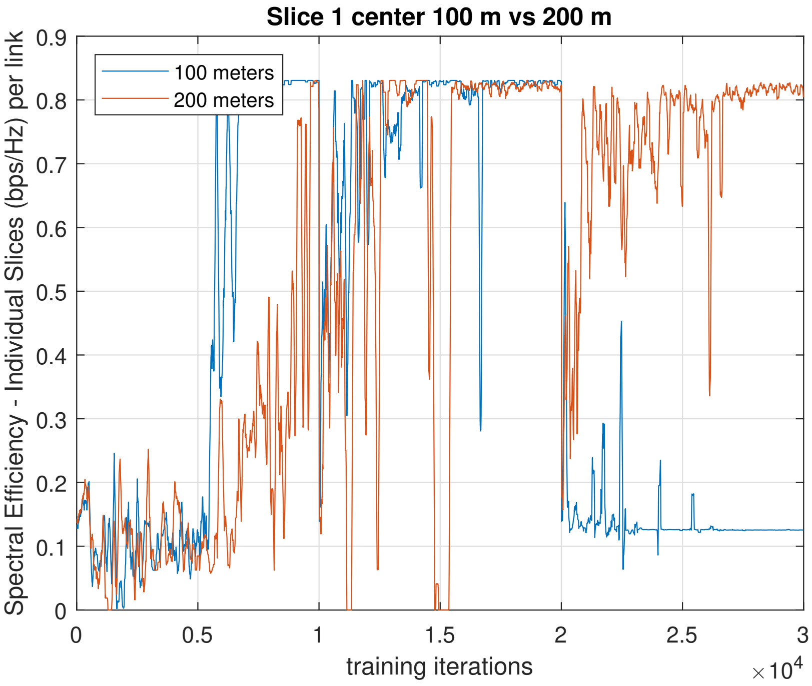

Figure 21: Slice 1 with users located in the center of the base stations comparing base station distances between 100 and 200 meters

In the slice number 2 the slices are quite equal compared to each other, as seen in figure 22

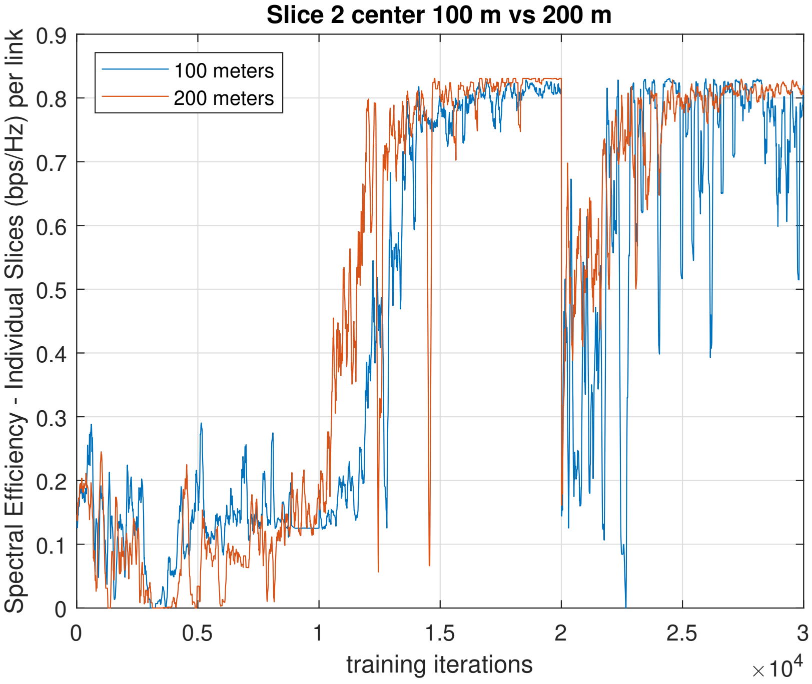

Figure 22: Slice 2 with users located in the center of the base stations comparing base station distances between 100 and 200 meters

The slice number 3 is shown in figure 23. The efficiency in the slice number three is quite same in both of the scenarios, only exception to that is at the end of the iterations where efficiency drops to zero in scenario with 100 meter base station distance.

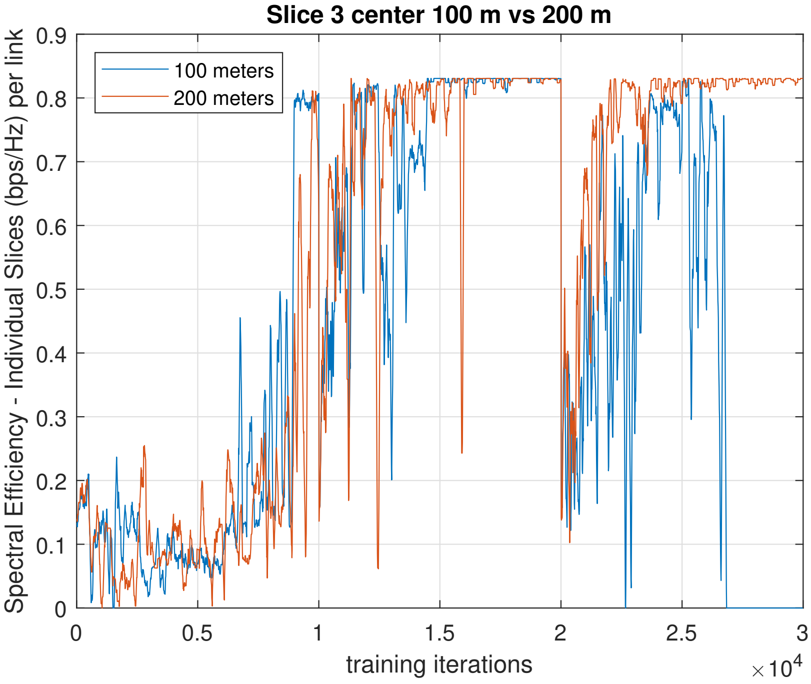

Figure 23: Slice 3 with users located in the center of the base stations comparing base station distances between 100 and 200 meters

The interference is shown in figure 24. The interference of 100 meter scenario is lower than 200 meter scenario for first two thirds in the simulation. At the last third of training iterations the scenario with 100 meter distance gets higher compared to the scenario with 200 meter distance.

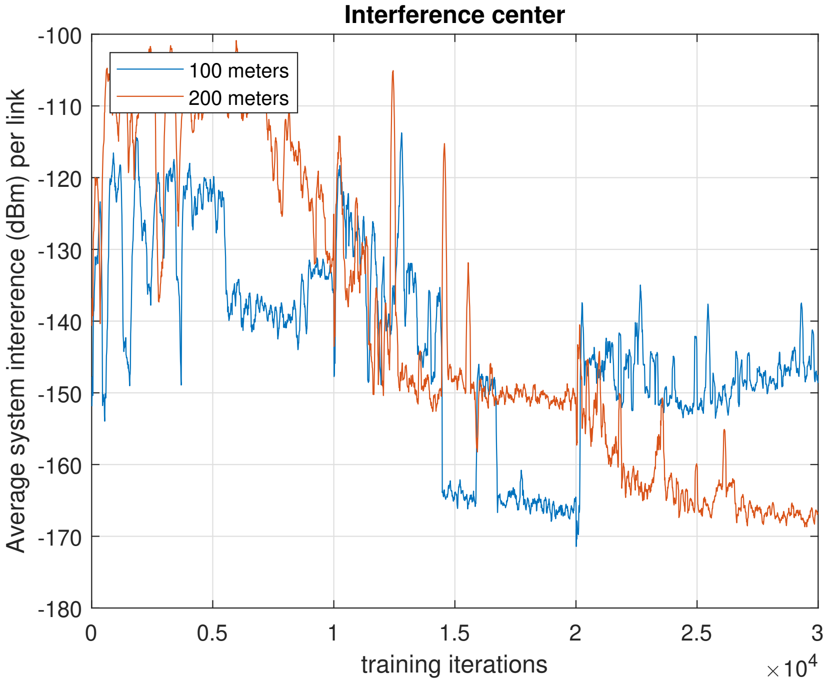

Figure 24: Interference with users located in the center of the base stations comparing base station distances between 100 and 200 meters

6.1.4 Fourth scenario - equal

In the fourth scenario the users are spread equally for all of these base stations.

The spectral efficiency of this scenario is shown in figure 25. The efficiency is at the begin a bit lower that reference in both scenarios. After first sixth of the simulation the both scenarios rise above the reference value and are quite equal compared to each other. In the middle of the simulation the 100 meter scenario has a bit higher efficiency compared to 200 meter distance. However it turns around in the last third of the simulation as 200 meter scenario gets higher compared to 100 meter scenario.

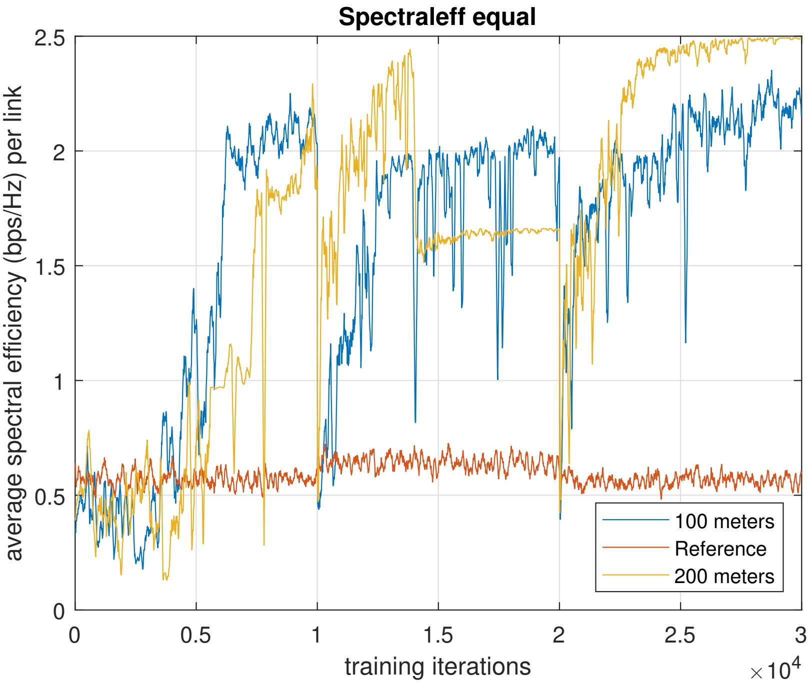

Figure 25: Spectral efficiency with users spread equally for the base stations comparing base station distances between 100 and 200 meters

The slice number 1 is shown in figure 26. The scenario with 100 meter distance has a higher efficiency in the first third of the simulation compared to the scenario with 200 meter distance. Otherwise the results of these scenarios are quite equal.

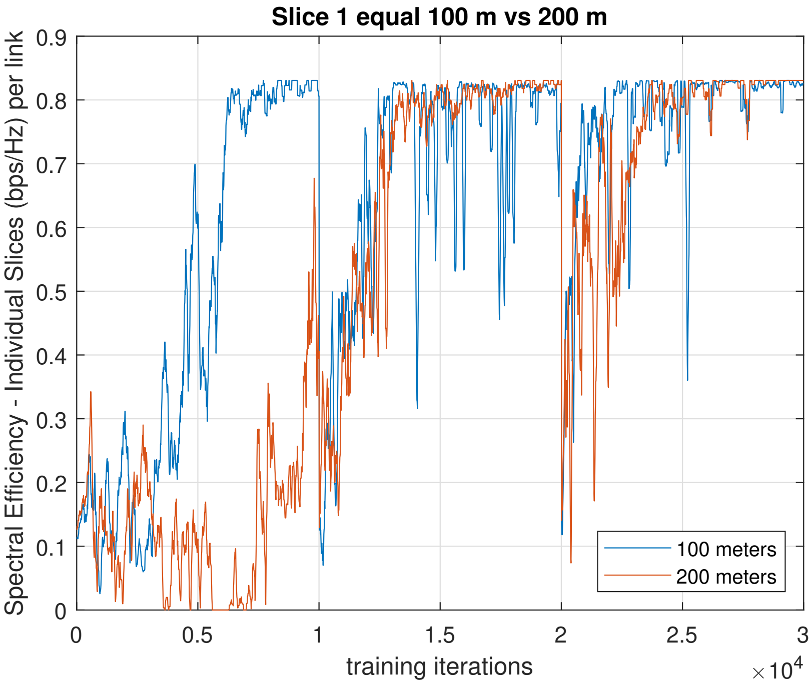

Figure 26: Slice 1 with users spread equally for the base stations comparing base station distances between 100 and 200 meters

In the second slice of this simulation the scenario with 200 meter base station distance has higher efficiency as shown in figure 27. Only for the first 5000 iteration rounds the scenarios are on the same level.

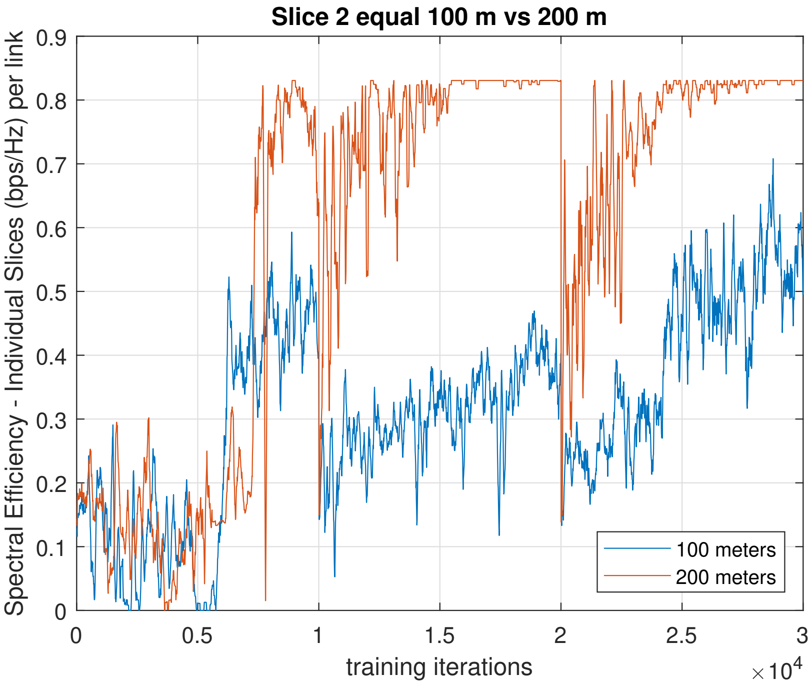

Figure 27: Slice 2 with users spread equally for the base stations comparing base station distances between 100 and 200 meters

The slice number 3 is shown in figure 28. In this slice the scenarios efficiencies are on the same level except the scenario with 200 meter distance at the iteration rounds from 14000 to 20000, where efficiency is 0.

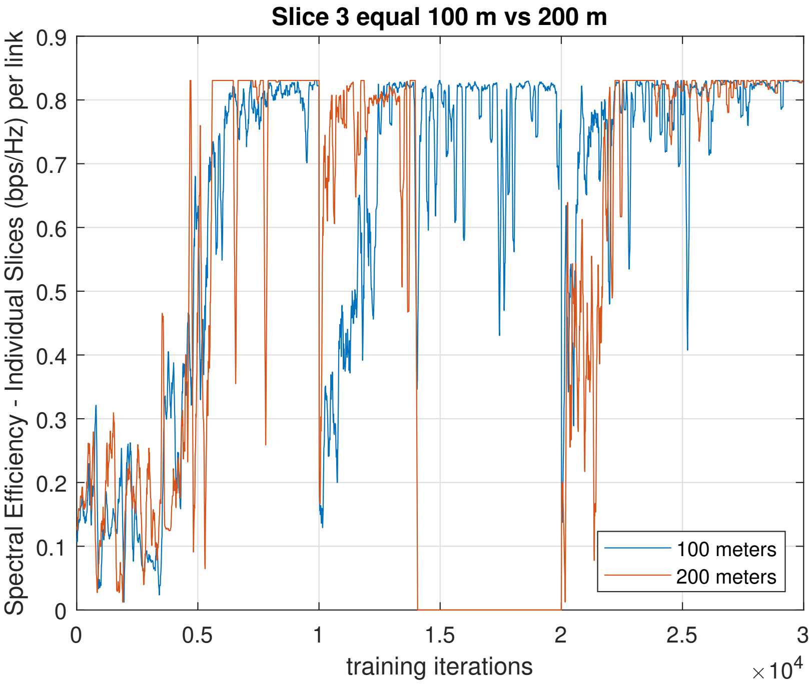

Figure 28: Slice 3 with users spread equally for the base stations comparing base station distances between 100 and 200 meters

The interference of this scenario is shown in figure 29. The interference of these scenarios are formed same way, only difference is that the scenario with 200 meter distance is about 50 dBm higher compared to the scenario with 100 meter distance.

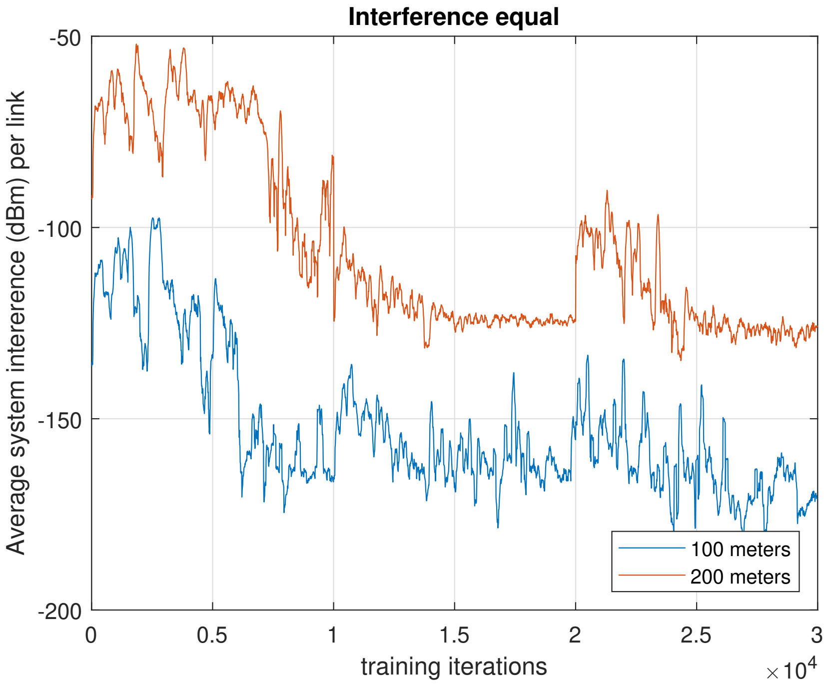

Figure 29: Interference with users spread equally for the base stations comparing base station distances between 100 and 200 meters

6.1.5 Comparing scenarios with in the same distance

Spectral efficiency of different scenarios with 100 meter base station distance is shown in figure 30. The scenario 1 (random) has the best efficiency. The others are quite equal to each other and they do depend on the sub scenario (one scenario has three sub scenarios, which do have same length). In the first sub scenario the scenario 2 (one) drops at iteration round 8000. At the last sub scenario the scenario 3 (center) drops after iteration round 26000.

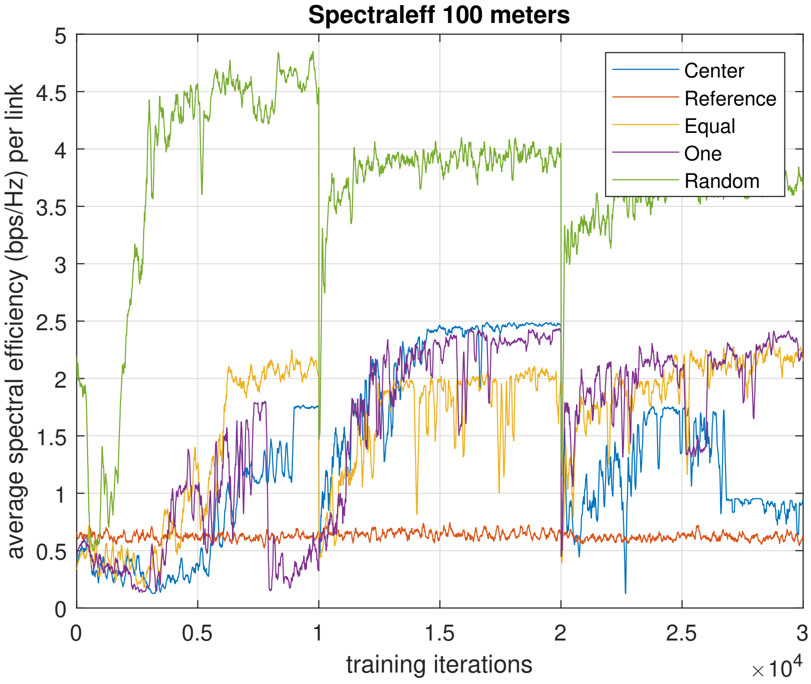

Figure 30: Spectral efficiency in different scenarios when distance between base stations is 100 meters

The slice number 1 of these scenarios is shown in figure 31. The scenario 2 (one) drops after the half on the first sub scenario. The scenario 3 (center) drops for the last third of the simulation and is only 0.12 while other two are at the level of 0.7 or 0.8.

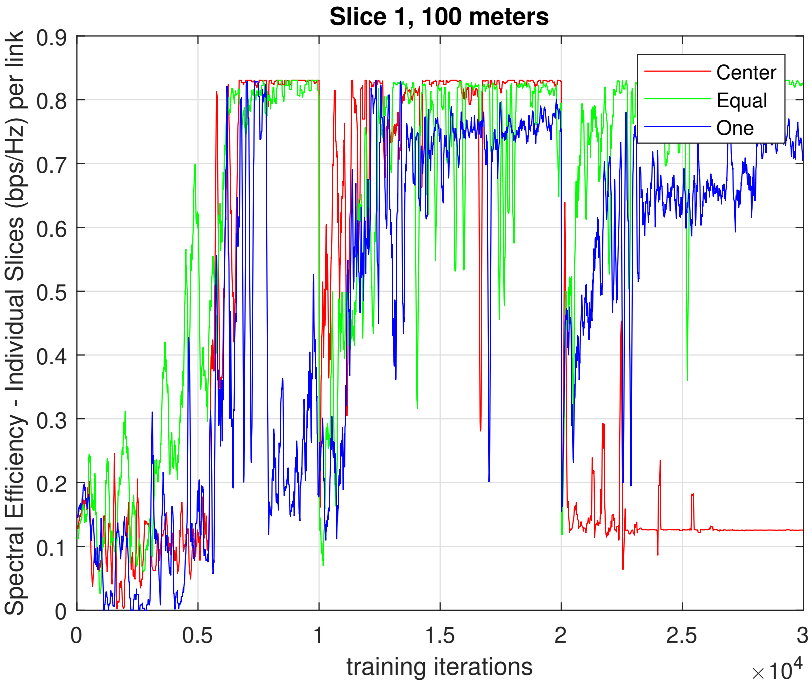

Figure 31: Slice 1 in different scenarios when distance between base stations is 100 meters

The slice number 2 of these scenarios is shown in figure 32. The scenario 2 (one) has better efficiency in the first third of the simulation. After that scenarios 2 (one) and 3 (center) are on the same levels. The scenario 4 (Equal) has a lot lower efficiency compared to the others.

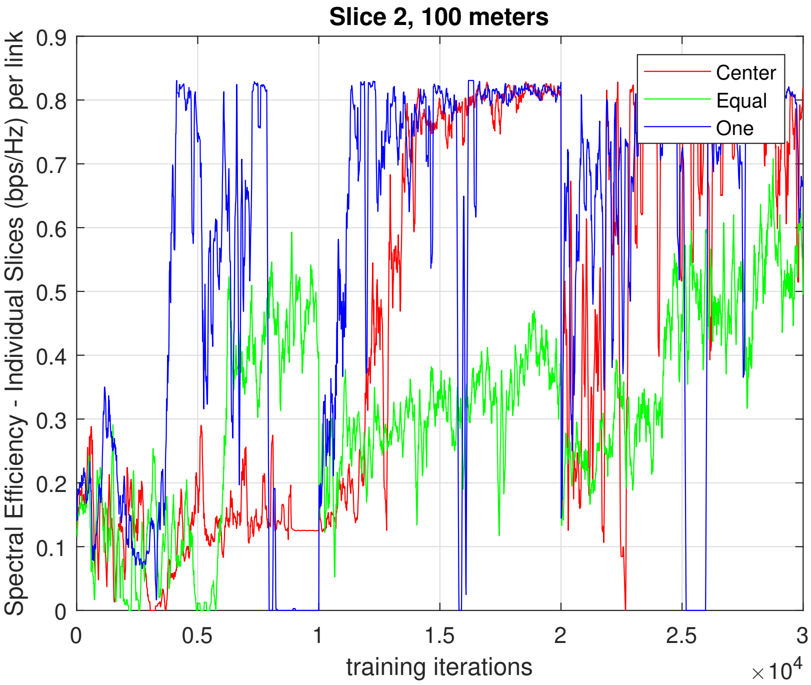

Figure 32: Slice 2 in different scenarios when distance between base stations is 100 meters

The slice number 3 of these scenarios is shown in figure 33. In this slice the scenario 4 (equal) has the best efficiency at the first third. In the second third the scenarios are all at the same level in efficiency. The last third of the simulation has a lot of oscillation, from 0.0 to 0.8. At the end of the simulation the efficiency of the scenario 3 (center) drops to 0 at the iteration round 27000.

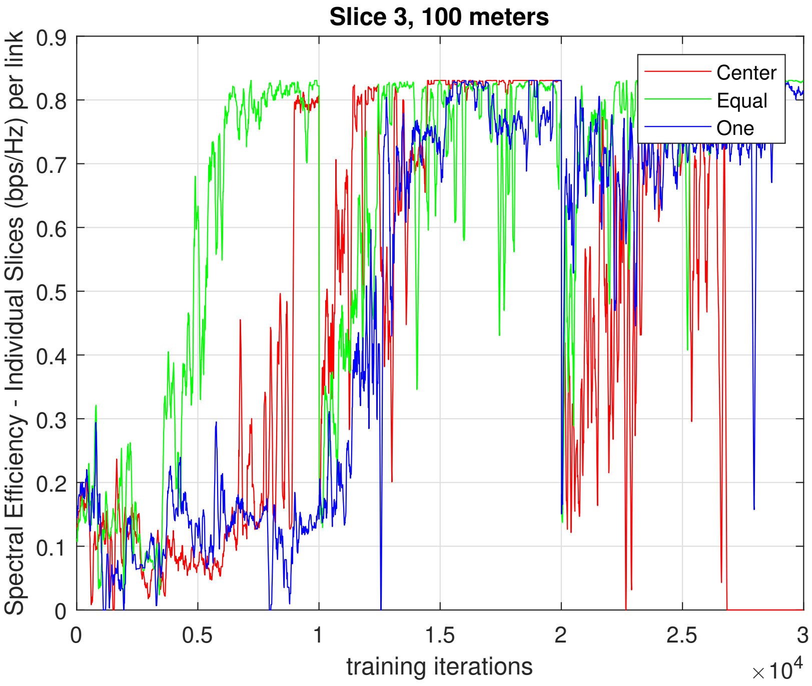

Figure 33: Slice 3 in different scenarios when distance between base stations is 100 meters

The interference of these scenarios is shown in figure 34. The scenario 2 (one) has the highest interference meanwhile the other four scenarios are at the same levels.

Figure 34: Interference in different scenarios when distance between base stations is 100 meters

The spectral efficiency of the scenarios with base station distance of 200 meters is shown in figure 35. As with the distance of 100 meters the scenario 1 (random) has the highest efficiency.

The scenario 2 (one) has lower efficiency than reference. The scenarios 3 (center) and 4 (equal) are having equal efficiencies except for the last half of the seconds third, where scenario 4 is having a lower efficiency than scenario 3.

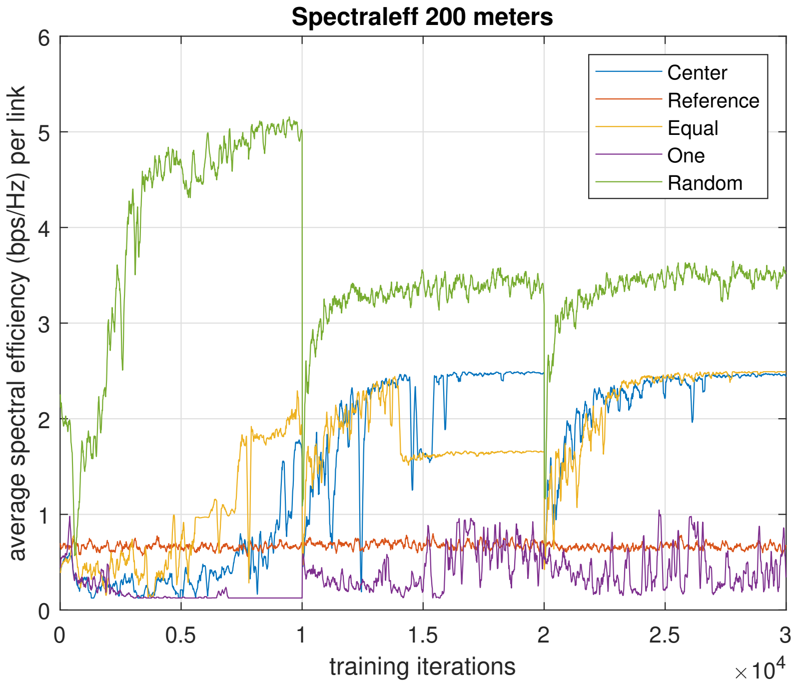

Figure 35: Spectral efficiency in different scenarios when distance between base stations is 200 meters

The slice number 1 of these scenarios is shown in figure 36. In this slice the efficiency of scenario 2 (one) is much lower compared to the other scenarios. The other scenarios are on the same levels by having the same ups and downs.

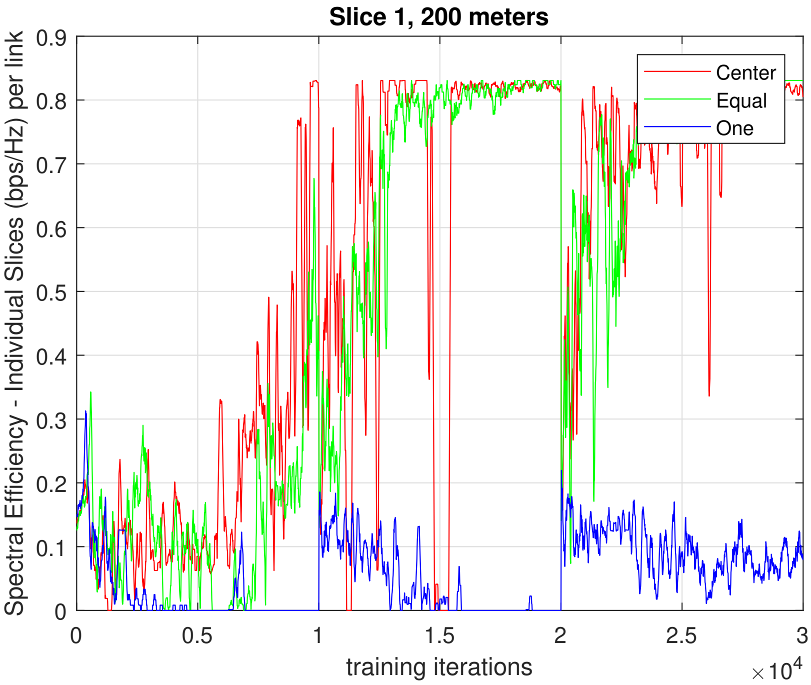

Figure 36: Slice 1 in different scenarios when distance between base stations is 200 meters

The slice number 2 of these scenarios is shown in figure 37. In this slice the scenario 2 (one) has lower efficiency compared to the other scenarios. The scenarios 3 (center) and 4 (equal) are on the same levels except the end of first third of this slice, when scenario 4 (equal) has significantly higher efficiency.

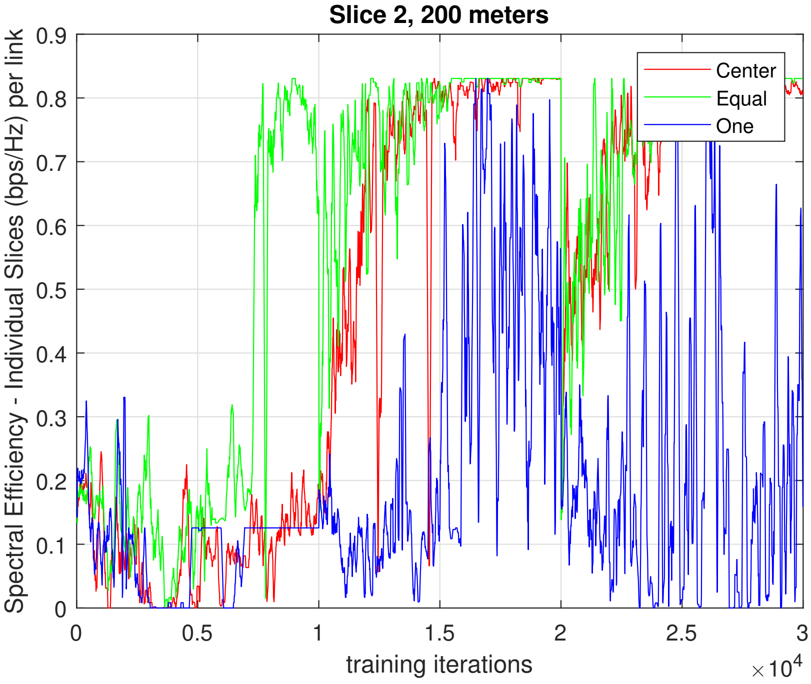

Figure 37: Slice 2 in different scenarios when distance between base stations is 200 meters

The slice number 3 of these scenarios is shown in figure 38. In the first third of this slice the scenario 4 (equal) has the highest efficiency. In the second third of this slice the scenario 3 (center) has the highest efficiency. The scenario 4 (equal) has equal efficiency in the first half of the second third compared to the scenario 3 (center). In the last third of this slice the scenarios 3 (center) and 4 (equal) are on the same levels. The scenario 2 (one) has the lowest efficiency in this slice.

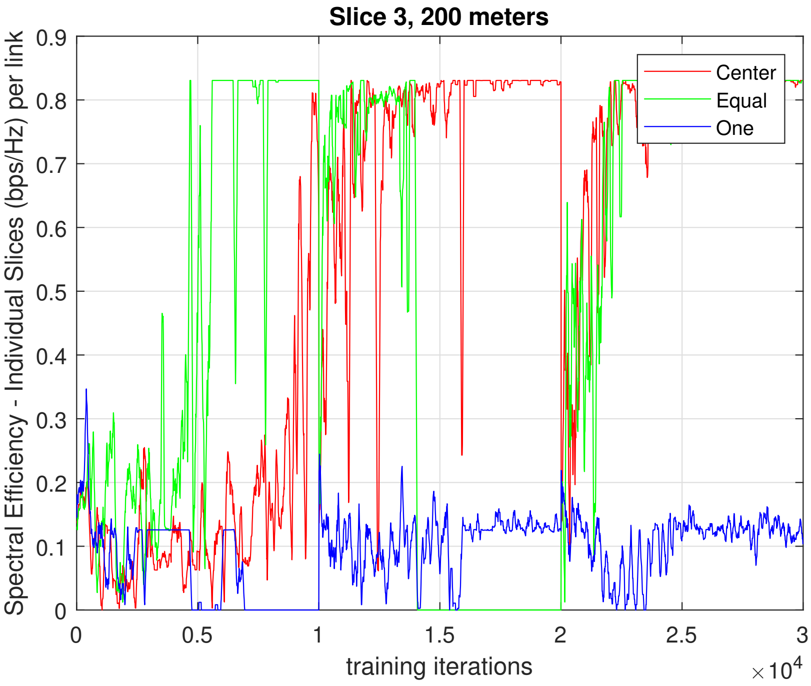

Figure 38: Slice 3 in different scenarios when distance between base stations is 200 meters

The interference of these scenarios is shown in figure 39. The scenario 2 (one) has the highest interference. The scenario 4 (equal) has the second highest interference in the first two thirds of this simulation. The scenario 3 (center) has the second lowest interference in the first half of the simulation and the lowest interference in the second half of the simulation. The scenario 1 (random) has the lowest interference in the first half of the simulation. In the last third of the simulation the interference of scenario 1 rises to the second highest.

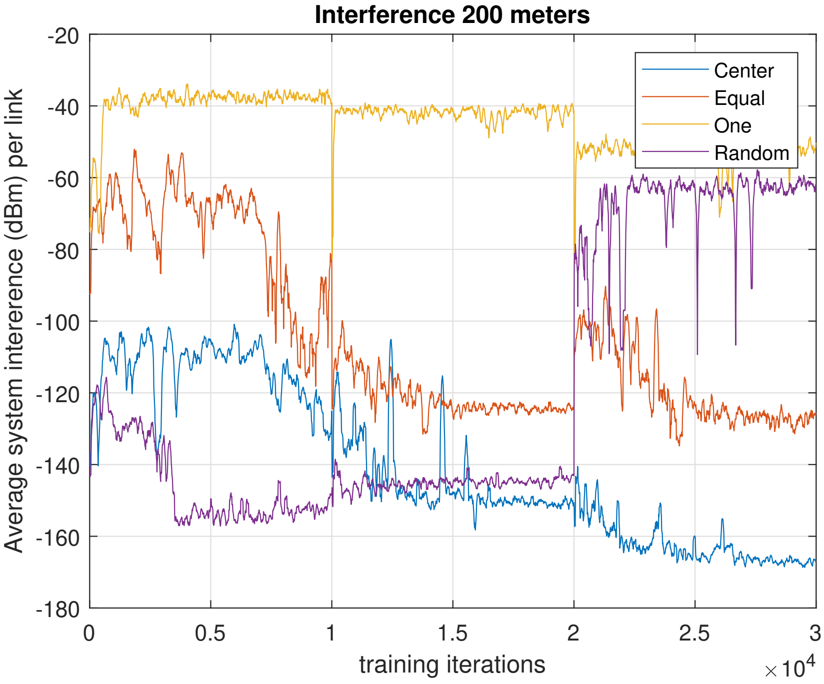

Figure 39: Interference in different scenarios when distance between base stations is 200 meters

6.2 Conclusions and Future Works

Based on the spectral efficiency metric of the system in these scenarios, almost every scenario was above reference. Only scenario 2 with base station distance of 200 meters has lower efficiency than reference value. The highest efficiency was with the simulator default values, the scenario 1 (random) with both base station distances. The reason for the highest efficiency in scenario 1 could be caused by the configuration of the simulator or by bug in the simulators client to base station mapping.

When talking about interference, there were big differences between the scenarios and distances. The interference with base station distance of 200 meters was in the area from -40 to -170 dBm. With the distance of 100 meters the interference was in the area from -80 to -180 dBm. The interference values were higher with greater distance.

In this thesis study, there were no sign that distance would be proportional with either spectral efficiency or with system interference. The effect of distance depended more on the scenarios and individual slices.

This research can be extended by taking the other traffic in the network into account. For example this could be added by increasing the number of messages and by adding the mobile users. This addition would need also adjusting the simulator by allowing manual user location definition and random user location at the same time. Also the simulator should be reviewed in case of any bugs when mapping users to base stations in custom user location.

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