UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola Tècnica Superior d'Enginyeria
de Telecomunicació de Barcelona

PERFORMANCE ASSESSMENT OF A RADIO ACCESS NETWORK AUGMENTED WITH USER EQUIPMENT ENABLED WITH RELAYING CAPABILITIES

A Master's Thesis

Submitted to the Faculty of the

Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona

Universitat Politècnica de Catalunya

by

Olga Ruiz Garcia

In partial fulfilment

of the requirements for the degree of

MASTER IN TELECOMMUNICATIONS ENGINEERING

Advisor: Jordi Pérez-Romero

Barcelona, May 2022

Title of the thesis: Performance assessment of a Radio Access Network augmented with User Equipment enabled with relaying capabilities.

Author: Olga Ruiz Garcia

Advisor: Jordi Pérez-Romero

Abstract

This Master's Thesis is encompassed in a vision of a Beyond 5G (B5G) scenario, where the User Equipment is exploited not only to satisfy the specific needs of the user, but also to augment the Radio Access Network (RAN) infrastructure. The research work has consisted in studying and analysing the deployment of a network using UEs as relaying devices in order to achieve an augmented RAN that will be able to offer a better performance to the users, including higher spectral efficiency, and lower outage probability. The conducted studies have consisted in performing variations on the configuration parameters of the network, as well as characterising the relay nodes, by means of simulations. The obtained results have then been analysed, evaluating them in terms of spectral efficiency and outage probability, and a specific relay activation strategy has been proposed, which has proven to introduce improvements in the network performance.

Acknowledgements

I would like to thank Jordi Pérez-Romero for guiding and helping me during the project development, as well as for being a great professor during the master and teaching me a great deal of what I know about mobile communication systems.

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

telecos BCN

Revision history and approval record

Revision	Date	Purpose
0	20/04/2022	Document creation
1	08/05/2022	Document revision
2	13/05/2022	Document revision
3	17/05/2022	Document revision

Written by:		Reviewed and approved by:	
Date	16/05/2022	Date	17/05/2022
Name	Olga Ruiz Garcia	Name	Jordi Pérez-Romero
Position	Project Author	Position	Project Supervisor

Table of contents

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

telecos BCN

List of Figures

List of Tables

1. Introduction

This Master Thesis has been carried out at the Signal Theory and Communications Department (TSC) of the Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona (ETSETB) at Universitat Politècnica de Catalunya (UPC).

1.1. Purpose

Wireless communications technology has been continuously growing and evolving since the 1980s, always changing and being updated in order to meet the increasing user needs. In recent years, wireless technologies have needed to support huge amounts of traffic and the demand is expected to grow. Operators have the challenge to upgrade wireless infrastructure, of which the biggest part corresponds to the Radio Access Network (RAN), so that all these requirements can be fulfilled.

The evolution has also reached User Equipments, which have achieved substantial computational capabilities.

Considering these trends, the developed thesis pictures a Beyond 5G (B5G) scenario where the UE is exploited not only to satisfy the specific needs of the UE owner but also to augment the RAN infrastructure. This way, UEs take a more active role in the network, and they are seen as an extended computing, storage and networking element of the B5G RAN infrastructure.

This evolution will bring diverse advantages, including the reduction of the number of BSs to deploy, enhancing the performance of the network regarding mitigating the impact of obstructing objects in outdoor mmWave scenarios, increasing capacity in high density areas and extending coverage in outdoor and indoor areas. All these benefits will cause the RAN to have a new degree of flexibility.

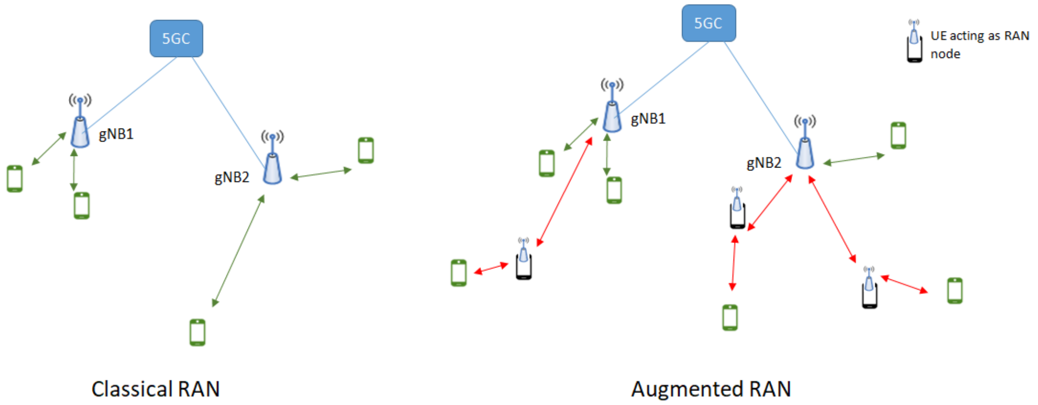


Figure 1.1: Classical RAN vs. Augmented RAN

The research carried out in this work involves the usage of UEs acting as relaying devices to augment the RAN infrastructure providing distributed capacity and network intelligence, as well as allowing coverage improvement without the need of deploying new cells.

All in all, the main goals of this thesis can be specified as follows:

- To analyse and evaluate, by means of simulations, the possible improvements that the described approach can provide to the network, in terms of coverage enhancements, and under various configurations.
- To characterise the relaying UEs according to different criteria, in order to identify the features of the most and least helpful relays.
- To enhance the used simulator platform for it to be able to perform the relay characterisation.
- To apply the results obtained from the stages above in order to develop an efficient way of managing the relays.

1.2. Methods and procedures

As it has been mentioned, this research work is based on performing a range of analysis by means of simulations. These have been carried out using a simulator platform that was already developed by the Mobile Communications Research Group from UPC.

Moreover, some enhancements have been added to the existing software in order to perform the wanted analysis.

1.3. Work Plan

Since this is a research thesis, a specific time plan was not defined for the whole duration of the project, and the followed paths have been developed according to the results obtained on previous phases.

Therefore, figures 1.2 and 1.3 show the work packages and the gantt diagram of the actual project development, specifying the different phases and how they have been distributed during the duration of the project.

		Name	Duration	Start	Finish	Predecessors
1		**⊟WP 1: Research and familiarization**	12 days?	**9/13/21 8:00 AM**	**9/28/21 5:00 PM**	
2		Reading of articles	12 days?	9/13/21 8:00 AM	9/28/21 5:00 PM	
3		Familiarization with simulator tool	12 days?	9/13/21 8:00 AM	9/28/21 5:00 PM	
4		**⊟WP 2: Configuration parameters variations**	32 days?	**9/29/21 8:00 AM**	**11/11/21 5:00 PM**	**3**
5		Number of BSs	11 days?	9/29/21 8:00 AM	10/13/21 5:00 PM	
6		BS transmission power	11 days?	10/7/21 8:00 AM	10/21/21 5:00 PM	
7		Relay Transmission Power	10 days?	10/14/21 8:00 AM	10/27/21 5:00 PM	
8		BS Frequency	11 days?	10/21/21 8:00 AM	11/4/21 5:00 PM	
9		Multihop	11 days?	10/28/21 8:00 AM	11/11/21 5:00 PM	
10		**⊟WP 3: Relay Characterization**	90.875 day...	**11/5/21 9:00 AM**	**3/11/22 5:00 PM**	
11		Code developement for relay characterization	20.875 days?	11/5/21 9:00 AM	12/3/21 5:00 PM	
12		Simulations Execution	5 days?	12/6/21 8:00 AM	12/10/21 5:00 PM	11
13		Results analysis	33 days?	12/13/21 8:00 AM	1/26/22 5:00 PM	12
14		Application of the obtained results - Relay selection	32 days?	1/27/22 8:00 AM	3/11/22 5:00 PM	12;13
15		**⊟WP 4: Relay Activation with Network Digital Twin**	46.875 day...	**3/11/22 9:00 AM**	**5/16/22 5:00 PM**	
16		New Database generation for timeframe 1	1 day?	3/11/22 9:00 AM	3/14/22 9:00 AM	
17		Relay characterization and ranking generation for timeframe 1	5.875 days?	3/14/22 9:00 AM	3/21/22 5:00 PM	16
18		Results applications in simulations for timeframe 1	6 days?	3/22/22 8:00 AM	3/29/22 5:00 PM	17
19		Results analysis	14 days?	3/30/22 8:00 AM	4/18/22 5:00 PM	18
20		New Database generation for timeframe 2	4 days?	4/19/22 8:00 AM	4/22/22 5:00 PM	
21		Relay characterization and ranking generation for timeframe 2	6 days?	4/25/22 8:00 AM	5/2/22 5:00 PM	20
22		Results applications in simulations for timeframe 2	6 days?	5/3/22 8:00 AM	5/10/22 5:00 PM	21
23		Results Analysis	4 days?	5/11/22 8:00 AM	5/16/22 5:00 PM	22
24		**⊟WP 5: Documentation**	147.875 da...	**11/1/21 9:00 AM**	**5/26/22 8:00 AM**	
25		Writing the thesis report	140.875 days?	11/1/21 9:00 AM	5/16/22 5:00 PM	
26		Upload Thesis report	0 days?	5/17/22 8:00 AM	5/17/22 8:00 AM	
27		Presentation	0 days?	5/26/22 8:00 AM	5/26/22 8:00 AM	1;4;10;15;25

Figure 1.2: Work packages and durations

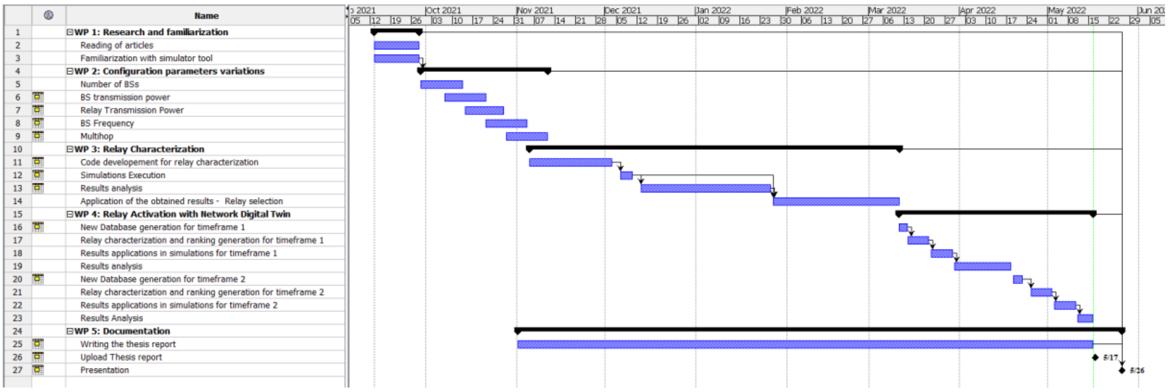


Figure 1.3: Gantt Diagram

1.4. Deviations from the initial plan

As it has been mentioned, there was no defined plan for the whole duration of the project. However, it is worth mentioning that, even if the ordinary deadline for the thesis presentation was the 9th of February, it was decided to present it according to the extended deadline, which was the 27th of May.

2. State of the art

2.1. O-RAN Architecture

From the perspective of the architecture, we can consider the project to be within the O-RAN architecture defined by the O-RAN Alliance. O-RAN architecture is designed to enable next generation RAN infrastructures and aims at achieving interoperability and standardisation of RAN elements including white box hardware, open source software and open interfaces, based on principles of intelligence, openness, disaggregation and virtualization.

Figure 2.1 shows the architecture defined by the O-RAN Alliance:

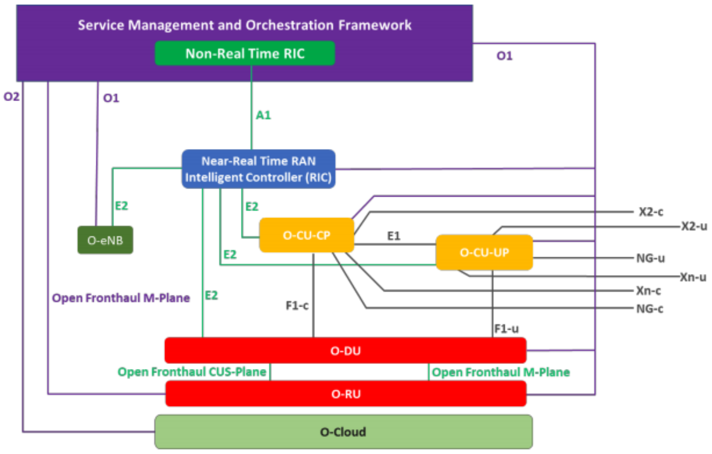


Figure 2.1: O-RAN Architecture [4]

RAN disaggregation splits base stations into different functional units, as shown in figure 2.2. The gNB is split into a Central Unit (CU), a Distributed Unit (DU), and a Radio Unit (RU) (called O-CU, O-DU, and O-RU in O-RAN specifications). The CU is further split into two logical components, one for the Control Plane (CP), and one for the User Plane (UP). This logical split allows different functionalities to be deployed at different locations of the network, as well as on different hardware platforms. [1]

From the protocol stack point of view, the split is done as follows:

- O-CU-CP: hosts the RRC and the control plane part of the PDCP protocol
- O-CU-UP: hosts the user plane part of the PDCP protocol and the SDAP protocol
- O-DU: hosts RLC/MAC/High-PHY layers based on a lower layer functional split.
- O-RU: hosts Low-PHY layer and RF processing based on a lower layer functional split.

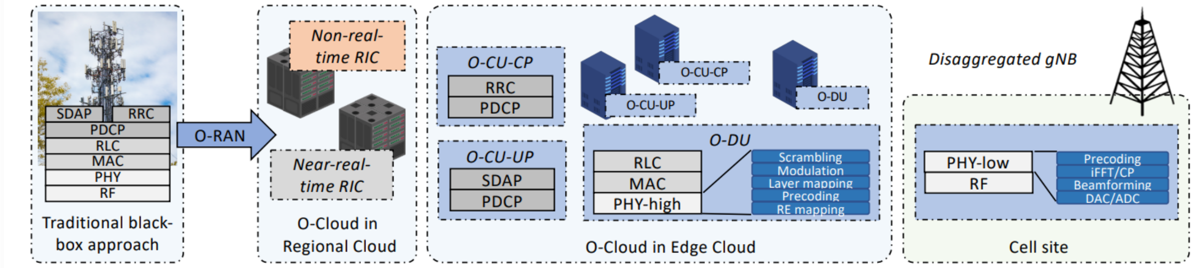


Figure 2.2: gNB Disaggregation [1]

Besides, the radio side also includes the near-real-time RAN Intelligent Controller which operates control loops. It interacts with DUs and CUs in the RAN, as well as with legacy O-RAN-compliant LTE evolved Node Bases (eNBs). Moreover, it is usually associated with multiple RAN nodes, so the near-RT closed-loop control can affect the QoS of hundreds or thousands of User Equipments. [3]

On the other hand, we find the Service Management and Orchestration (SMO) Framework, which includes the non-real-time (or non-RT) RIC.

The SMO platform is an intelligent automation platform which applies automation at scale to simplify the complexity of networks, as well as improve network performance, enhance customer experience and minimise RAN operational costs. The architecture defines various SMO interfaces, namely O1, O2, and A1, which allow the SMO to manage multi-vendor Open RAN networks:

- O1: Interface between management entities in SMO Framework and O-RAN managed elements, for operation and management.
- O2 : Interface between SMO Framework and Infrastructure Management Framework supporting O-RAN virtual network functions.
- A1: Interface between non-RT RIC and near-RT RIC. Over this interface non-RT RIC performs policy management, enrichment information and AI/ML model updates on the near-RT RIC. [2]

Non-RT RIC complements the near-RT RIC for intelligent RAN operation and optimization on a time scale larger than 1 second. Besides, it also enables AI/ML workflow including model training and updates, and policy-based guidance of applications/features in near-RT RIC. [3]

2.2. Relaying

The concept of relaying was introduced in LTE-Advanced (Release 10), and it enables the transmitted signals to be relayed by some specific nodes called relay nodes (RN), in order to enhance coverage and signal quality. This way, the link between the BS and the UE is divided in two hops: The link between the BS and the relay, called the backhaul link, and the link between the relay and the UE, called the access link. Besides, the cell to which the relay is connected using the backhaul link is known as the donor cell, and the cell that the relay creates is known as the relay cell. [7]

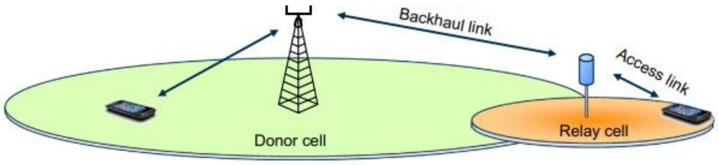


Figure 2.3: Scheme of access and backhaul links [5]

Relaying is different to using a repeater which re-broadcasts the signal. Relays actually receive, demodulate and decode the data, apply any error correction to it and then retransmit a new signal, so that it does not suffer degradation. [6]

Relays can be helpful in different scenarios:

- Increase network density: Relay nodes can be easily deployed in situations where the aim is to increase network capacity by increasing the number of BSs to ensure good signal levels are received by all users. Relays are easy to install as they require no separate backhaul and they are small enabling them to be installed in many convenient areas.
- Network coverage extension: Relays can be used as a method of filling small holes in coverage. With no need to install a complete base station, the relay can be quickly installed so that it fills in the coverage blackspot.

Relays can be classified in two operation modes, according to the carrier frequency they operate on:

- Inband: The backhaul link and the access link use the same spectrum. This may require additional mechanisms to avoid interference between the access and backhaul links, such as separation in the time domain.
- Outband: Backhaul link and access link operate on separate spectrums.

On the other hand, relays can be classified in two types:

- Type I relays (non-transparent): They send their own control information and their Cell ID is different from the donor Cell ID.
- Type II relays (transparent): They share the Cell ID and the control messages with the donor eNB, so the UE is not aware that it is connected to the BS through a relay. [6]

2.2.1. Integrated Access Backhaul (IAB)

In the context of relaying, one of the possible approaches to introduce the technology is Integrated Access Backhaul (IAB).

Integrated Access Backhaul is a technology introduced by the Third Generation Partnership Project (3GPP), which consists in providing flexible wireless backhauling using 3GPP new radio (NR) technology in international mobile telecommunications (IMT) bands, providing not only backhaul but also the existing cellular services in the same node [8]. With this technology, only a few next generation node bases need to be connected to traditional fibre infrastructures, while the others wirelessly relay the backhaul traffic, possibly through multiple hops and at mmWave frequencies [9]. IAB presents lower deployment costs and complexity compared to the all-wired setup.

Figure 2.4 shows the system architecture, where multiple fixed IAB-nodes use wireless backhaul, and IAB-donors have fibre connectivity toward the core network. IAB-nodes and IAB-donors can serve UEs and other IAB-nodes. This configuration yields the most limited impact on the core network and signalling overhead, and the lowest relay complexity and processing requirements. [9]

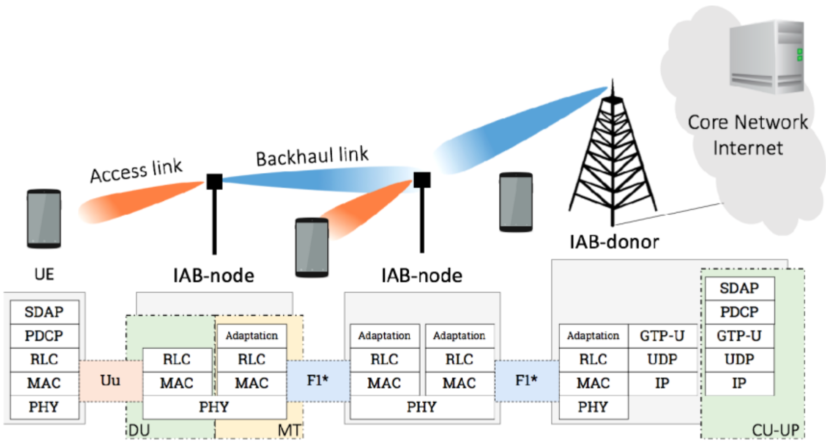


Figure 2.4: IAB Architecture [9]

2.2.2. RF Layer Relays

An alternative type of relaying technology are relays that only work at the RF layer. In this category we can find a special type of relay called Smart Repeaters.

They are an evolution of the more classical RF Repeater, which has been used in 2G, 3G and 4G deployments to supplement the coverage provided by regular macro cells. Classical RF Repeaters are low-cost, easy to deploy, and do not increase latency. On the other hand, as they amplify both signal and noise, they can contribute to an increase of interference in the system.

Smart Repeaters are a new type of network node that are able to make use of some side control information to enable a more intelligent amplify-and-forward operation in a system with time-division duplex (TDD) access and beamforming operation.[10]

2.3. UE-to-Network relays

As it has been mentioned, the usage of relaying nodes offers a great deal of advantageous possibilities, such as extending network coverage and capacity or deploying mobile cells. Besides, the technological evolution introduced by 5G and beyond systems, thanks to a larger available bandwidth in mmWave bands, has brought the adequate conditions to further develop the relaying concept.

In the Beyond 5G (B5G) context, one of the proposed developments involves the usage of UEs acting as relays to augment the RAN infrastructure providing distributed capacity and network intelligence. This means that UEs will take a more active role in the network and they will complement the RAN infrastructure.

This evolution will bring diverse advantages, including the reduction of the number of BSs to deploy, enhancing the performance of the network regarding mitigating the impact of obstructing objects in outdoor mmWave scenarios, increasing capacity in high density areas and extending coverage in outdoor and indoor areas. All these benefits will cause the RAN to have a new degree of flexibility.

This way, a more dynamic and adaptable RAN is envisioned, which is augmented by the networking, computing and storage resources brought by UEs. [11]

We find several approaches in order to introduce relaying technologies at UEs, such as the usage of D2D communications as a part of Proximity Services (ProSe), or a more futuristic method involving UEs that support the capabilities of IAB nodes.

2.3.1. Device-to-Device (D2D) communications

Fixed terminal relaying brings improvements in cellular systems, but it is the implementation of device relaying that allows the technology to achieve its full potential. The term device refers to a cell phone or any other portable wireless device with cellular connectivity (tablet, laptop, etc) a user owns. Device relaying makes it possible for devices in a network to function as transmission relays for each other. This is possible with device-to-device (D2D) communication functionality. [13]

Device-to-Device communications were first introduced by 3GPP as a part of the Proximity Services concept. D2D communication in cellular networks is defined as direct communication between two mobile users without traversing the Base Station (BS) or core network. D2D communication is generally non-transparent to the cellular network and it can occur on the cellular spectrum (i.e., inband) or unlicensed spectrum (i.e., outband).

D2D communications offer several advantages, such as improving spectral efficiency, throughput, energy efficiency, delay, and fairness. [12]

In the context of LTE, Proximity Services and thus, D2D communications, define a new interface, PC5 interface, associated with the link between two UEs, called sidelink.

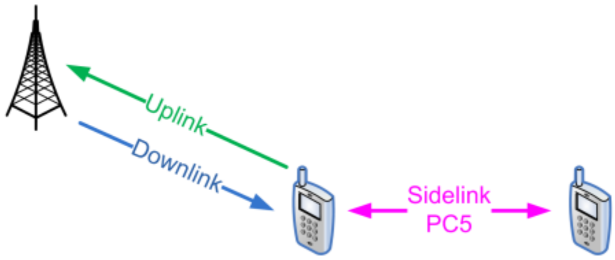


Figure 2.5: D2D communications links [14]

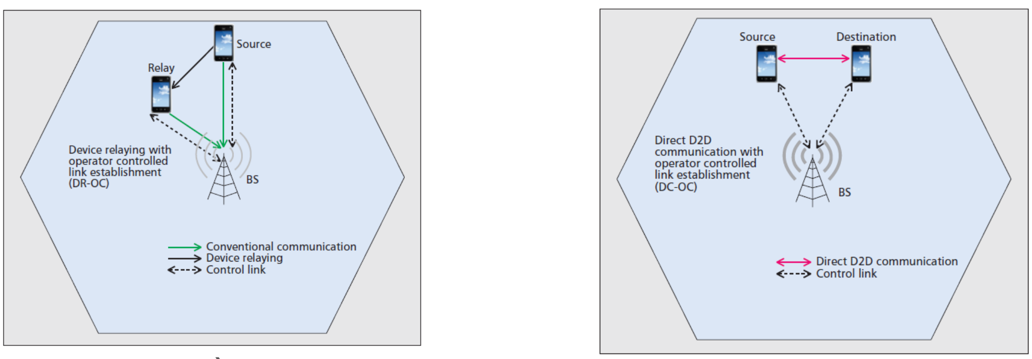
When carrying out D2D communications, the operator might have different levels of control. It may have full/partial or none control over the resource allocation among source, destination, and relaying devices. Therefore, we can define the following four main types of D2D communications [13]:

- Device relaying with operator controlled link establishment (DR-OC): A device at the edge of a cell or in a poor coverage area can communicate with the BS through relaying its information via other devices. This allows for the device to achieve a higher QoS or more battery life. The operator communicates with the relaying devices for partial or full control link establishment (Fig. 2.6 a).

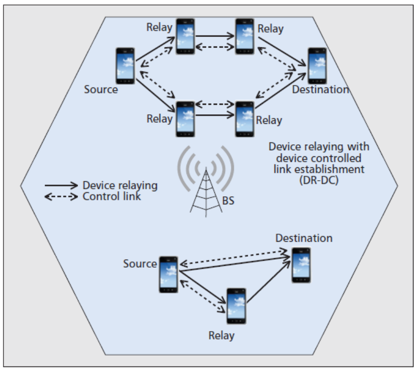
- Direct D2D communication with operator controlled link establishment (DC-OC): The source and destination devices talk and exchange data with each other without the need for a BS, but they are assisted by the operator for link establishment (Fig. 2.6 b).

- Device relaying with device controlled link establishment (DR-DC): The operator is not involved in the process of link establishment. Therefore, source and destination devices are responsible for coordinating communication using relays between each other (Fig. 2.6 c).

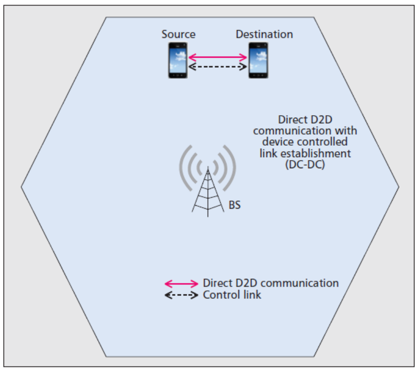
- Direct D2D communication with device controlled link establishment (DC-DC): The source and destination devices have direct communication with each other without any operator control. Therefore, source and destination devices should use the resource in such a way as to ensure limited interference with other devices (Fig. 2.6 d) .



a) b)



c)



d)

Figure 2.6: D2D communications types [13]

In the same way as the relays, D2D communications can be classified according to the spectrum in which they are working and they can be inband or outband [12].

- Inband D2D:

  This category uses cellular spectrum for both D2D and cellular links. The motivation for choosing inband communication is usually the high control over cellular spectrum, since the interference in the unlicensed spectrum can be harder to control. This imposes QoS constraints.

  Inband communication can be further divided into underlay and overlay categories. In underlay D2D communication, cellular and D2D communications share the same radio resources. On the other hand, D2D links in overlay communication are given dedicated cellular resources.

  The main advantage of inband D2D is that it can improve the spectrum efficiency of cellular networks, whether by reusing spectrum resources or allocating dedicated cellular resources. The major disadvantage, however, is the interference caused by D2D users to cellular communications and vice versa. This interference can be reduced by introducing high complexity resource allocation methods, which increases the computational overhead of the BS or D2D users.

- Outband D2D:

  In this case D2D links use a different spectrum band than cellular links, thus eliminating the interference issue between each other. This can be done by using unlicensed spectrum or using other wireless technologies such as WiFi Direct, ZigBee or Bluetooth.

  Outband D2D can be further classified as controlled and autonomous. In controlled D2D, the cellular network controls the D2D radio interface. In autonomous D2D, on the other hand, D2D links are controlled by the users.

  The disadvantage of outband D2D, however, is that it may suffer from the uncontrolled nature of unlicensed spectrum.

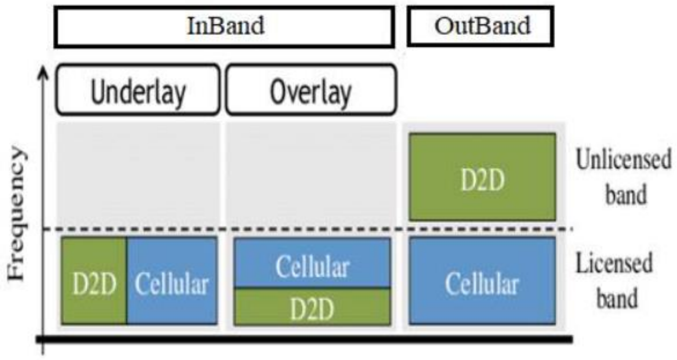


Figure 2.7: Inband and outband D2D communications. [15]

3. Methodology / project development

This thesis has consisted in studying and analysing the deployment of a network using UEs as relaying devices in order to achieve an augmented RAN that will be able to offer a better performance to the users, including higher spectral efficiency, which results in higher capacity for a user, and lower outage probability.

Research has been conducted involving the impact of the network parameters' configuration, an analysis and characterisation of the relay UEs, as well as a study of the effect of the selection of the activated relays according to different criteria.

All these studies have been carried out using a simulator developed in matlab. The following section describes the features of this simulator.

3.1. Simulator Tool

3.1.1. Scenario

The simulations carried out in the development of this work recreated a scenario of an urban sector in the city of Barcelona, which has an area of 0.5 km^2 (700m x 700m). The region includes streets, buildings and parks, so diverse environments are represented in it.

Figure 3.1: Map of the simulation scenario

The user density in this area is 43300 inhabitants/km^2, so, if we assume an operator with a 20% market penetration, we can consider that the resulting density is 8660 UEs/km^2, which leads to having approximately 4330 UEs in the selected area.

The simulator creates a model of the region, which contains 22 separate buildings and where each of the buildings is 7 floors high. The height of each floor is 3.5 m.

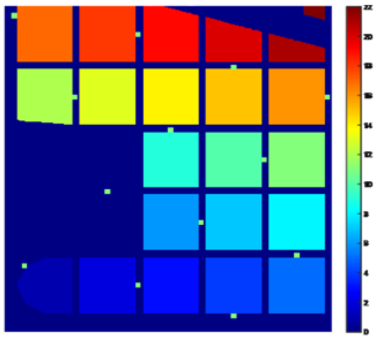


Figure 3.2: Representation of the buildings in the scenario

Besides, the simulator allows varying the number of base stations that will be involved in the simulations. The following images show the positions of the base stations in the cases of having 13, 6 and 3 BSs.

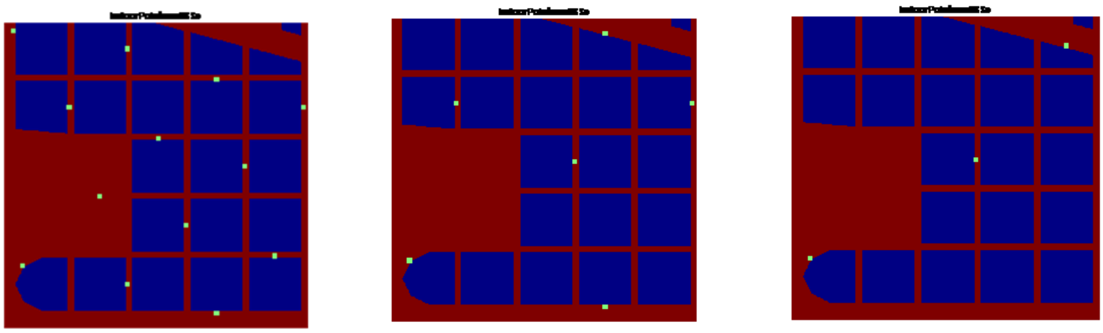


Figure 3.3: Representation of the BSs in the scenario

3.1.2. User categories

In the actual simulation process, a group of users are launched, which belong to one of the following categories: pedestrians, cars and stationary UEs. Pedestrians move at a speed of 3km/h and can be located following the sidewalks of the different streets or walking around the park areas. Vehicles, on the other hand, move at 30km/h along the streets. Finally, stationary UEs can be located in indoor or outdoor environments and they are the ones that will be subject to be used as relays, so we can classify them as Stationary Relay UEs and Stationary non-Relay UEs.

The relays will be selected from a database that initially contains 20000 different relays with fixed positions and pre-calculated propagation values, which help make the simulation process faster.

The simulator sets a total number of UEs and defines the percentage of the users of each type. The total number of users and the ratios of each of the user types are specified in the following table:

Total	4300 Users
Pedestrians	0.5
Stationary UE	0.4
Cars	0.1

Table 3.1: Ratio of each user category

The number of available relays is then defined through the Involvement Factor parameter (F) which indicates the percentage of stationary UEs that will act as relays. In our simulations, it is set to take the values specified in the following table:

F	1	2	5	10	20	50	80
N_Relays	22	43	108	215	430	1075	1720

Table 3.2: Number of relays for each F value

3.1.3. Simulation Process

The simulation process is carried out following a set of steps:

- A number of relays (defined by the involvement factor and the stationary UE ratio) are selected randomly from the relay database, which will be available to serve the rest of the UEs during the whole simulation. These relays need to be ensured to be valid, meaning that they need to be located at positions that are not in outage, getting a spectral efficiency higher than 1 b/s/Hz from their serving BS. The concept of outage is more thoroughly explained in section 3.3.2.
- During the simulation, each user category generates a session according to a Poisson generation model. The generation rate for each category corresponds to the number of users of the category multiplied by the session generation rate of the UEs. The session duration is an exponential random variable with a defined average. For each generated session, each category proceeds in a different way:
    - Pedestrians and cars: A random valid location is chosen and the user starts moving according to its model. The description of valid locations for each user type is further explained in section 3.1.7.
    - Stationary non-relay UEs: A random indoor or outdoor location is chosen, which will be retained during the whole session. Stationary UEs can be located anywhere in the scenario, except at the centre of the streets, which represent the roads for vehicular UEs.
    - Stationary relay UEs: They are randomly associated with one of the relays selected in the simulation. When a session is active for a relay, it means that the UE generates its own traffic in addition to the traffic it relays from other UEs. However, when the session ends the relay remains available for other UEs.
- The UEs that have an active session move according to their model and they connect to the best BS or relay that serves the position where they are at. Cars, however, can only be served by BSs.

- Once the simulation is over, a set of statistics are stored. After multiple realisations of the simulations with different relay and UE configurations, those statistics can be averaged.

It needs to be noted that the simulations only consider downlink traffic.

The parameters defined for the elements that take part in the simulations are specified in the following table:

BS	
Antenna Gain	26 dB
Tx Power	25 dBm
Bandwidth	100 MHz
Frequency	26 GHz
Height	10 m
Relay	
Antenna Gain	3 dB
Tx Power	25 dBm
Bandwidth	100 MHz
Frequency	3.5GHz
Min. Spectral Eff	1 b/s/Hz
UE	
Session Rate	1 sess./h
Avg. Session Duration	300 s
Direct Link	
Antenna Gain	10 dB
Noise Figure	9 dB
Max. Spectral Efficiency	7.4063 b/s/Hz
Min. Spectral Efficiency	0.2344 b/s/Hz
Relay Link	
Gain Antenna Relay-UE	3 dB
Spectral Efficiency Limit Outage	1 b/s/Hz

Table 3.3: Simulation parameters

3.1.4. Connectivity Model

In order to decide whether the UE will be connected to a relay or to the BS, for a UE which is located at a given position of the scenario, we compute the SNR and the spectral efficiency of the direct link, as well as the SNR and the spectral efficiency when the UE is connected through a relay. The latter are calculated as the minimum SNR and spectral efficiency between the access link and the backhaul link.

Having computed those values, the UE will be served by the BS or relay that provides the highest SNR. This, however, does not apply to the vehicles, which will always be served by BSs.

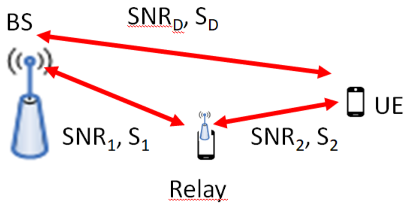


Figure 3.4: Direct, Backhaul and Access links

Spectral efficiency and SNR are related by the Shannon formula, but they are bounded according to the maximum and minimum levels defined by the MCSs of 5G NR. Then, the maximum spectral efficiency is 7.4063 b/s/Hz and the minimum is 0.2344 b/s/Hz (points with spectral efficiency lower than this value are assumed to have 0 b/s/Hz).

Furthermore, it needs to be mentioned that the relays in the simulation are out-of-band relays, which means that the relay-UE link and the BS-UE link use different frequencies.

3.1.5. Propagation Model

The simulator defines two different propagation models, one for the BS-UE or BS-relay links and a different one for the relay-UE links.

- BS-UE and BS-relay links:

They use the UMi model of [16]. In it, LOS and NLOS points are determined taking into account the positions of the buildings and the LOS probability defined by the model, spatially correlated shadowing is contemplated and Outdoor to Indoor losses are considered for indoor points.

- Relay-UE links:

They use the D2D model defined in [17]. Additionally, an indoor-to-outdoor loss is considered for the cases where one of the UEs is indoor and the other outdoor. Besides, for indoor UEs located at different floors, an additional floor penetration loss is added.

Besides, the simulator assumes that the interference among cells is negligible due to the large amount of spectrum available in the 26 GHz band, which facilitates deployments with low frequency reuse, and also due to the interference coordination that can be achieved when transmitting with narrow antenna beams.

3.1.6. Mobility Model

- Pedestrians

As it has been mentioned before, pedestrians can only be located on sidewalks of streets or pedestrian areas. These valid points are depicted in red in the map shown in figure 3.5.

When they are on a sidewalk, they follow the street in one of its two directions, which is chosen randomly. When they arrive at an intersection with another street, they might change to the new street or continue on the current one according to a given probability (prob_change_inters_ped). When the edge of the scenario is reached, the user changes its direction.

When they are in a pedestrian area (e.g. a park), on the other hand, they follow a random walk model: the direction is randomly chosen, and in each time step a probability is applied to decide if the UE changes direction. If it decides to change, the new direction is chosen in the range (-45º, +45º) with respect to the current one.

Users can move from a sidewalk to a pedestrian area or the opposite.

- Vehicular UEs

Vehicular users can only be located on the centre of the streets. Valid points are depicted in the map below.

Each street has a defined direction, which the UE will follow. When it reaches an intersection with another street, it decides to change to the other street according to a given probability. When the user reaches the edge of the scenario, its session stops.

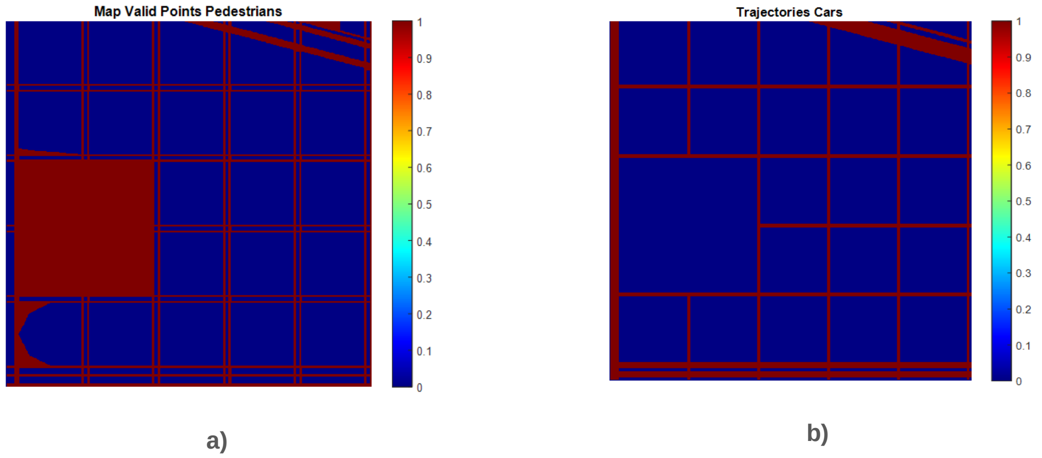


Figure 3.5: Maps of valid points for pedestrians (a) and cars (b)

3.1.7. Collected statistics

As it has been said, the simulations collect a set of performance indicators for every user type. All the statistics are separately collected for each user type, and, in the case of stationary UEs (relays or non-relays) they are also split between indoor or outdoor users.

Those indicators are the following:

- Spectral efficiency (bits/s/Hz) observed by the UEs:

  The spectral efficiency specifies the information rate that can be transmitted over a given bandwidth in a communication system. It is a measure of how efficiently a limited frequency spectrum is used. It is measured in bit/s/Hz.

  It corresponds to the net bit rate (useful information rate excluding error-correcting codes) or maximum throughput divided by the bandwidth in hertz of a communication channel or a data link.

  $$Spectral\ Efficiency = \frac{Throughput\ (bps)}{Bandwidth\ (Hz)}$$

  The spectral efficiency is obtained based on the Shannon formula as:

  $$S.\ Eff = log_2(1 + SNR)$$

  Where the SNR is the signal to noise ratio of the corresponding link, explained in section 3.1.4.

  From this metric, the following values are collected:
  - Average value
  - Percentiles 5 and 95
  - CDF

- Outage probability:

  The outage probability of a communication channel is the probability that a given information rate is not supported, because of variable channel capacity. It is defined as the probability that the information rate is less than the required threshold information rate. It is also the probability that an outage will occur within a specified time period, which means that the receiver is considered to be out of range of the BS.

- Duration of the connection time to a BS:
  - Average value
  - Percentile 5 and 95
  - CDF

- Duration of the connection time to a relay:
  - Average value

  - Percentile 5 and 95
  - CDF

- Probability of connecting to a relay

3.2. Developed studies

The work that has been carried out during the development of the thesis has consisted in several phases.

On the one hand, the first stage consisted in the familiarisation with the simulation tool in order to understand how it worked, and how to correctly collect and analyse the simulation data.

Next, different sets of simulations were performed varying some of the configuration parameters of the network deployment, and analysing the results in order to evaluate the impact that those changes have on the overall performance of the network. The simulation sets consisted in carrying out 50 simulations, which are 10000 seconds long, for each of the arranged configurations and for each value of the involvement factor F. The results from the 50 simulations are then averaged to obtain the final statistics. This analysis is further explained in section 4.

Afterwards, a new phase started, which consisted in carrying out a deeper analysis of the relays themselves, characterising them in order to evaluate their effect on the network and know how useful they are to the connected UEs. The relays were characterised according to three criteria:

- Number of UEs served by the relay
- Introduced spectral efficiency improvement
- Number of UEs served by the relay that were in outage with their serving BS.

This phase involved enhancing the simulation code in order to count the number of users that are connected to each of the relays at every moment of a simulation, as well as to identify the spectral efficiency improvement introduced by the relay for each UE. The introduced enhancements consisted in monitoring the specified criteria at every time step and for every active relay of the simulation, taking into account the different user categories. All the statistics are then averaged in order to obtain single values for each relay. Furthermore, the needed code for plotting the desired relays at the map has been developed, in order to be able to analyse their positions.

This characterisation process allowed creating a ranking of the relays according to their usefulness. That ranking was then used to perform new sets of simulations varying the number of active relays, with the aim of checking how the selection of the best relays helped the network. The analysis and the obtained results of this phase are more deeply explained in section 5.

Finally, the concept of the relay ranking was further developed to formulate a relay selection strategy and its possible practical implementation based on a network digital twin. The idea is to consider the actual simulator used in the studies as a network digital twin that models the network behaviour and allows offline characterisation of the ranking of the candidate relays. This process could be somehow similar to conducting an offline training of a relay selection strategy.

This phase used a more reduced and more realistic relay database, containing 4300 relays, instead of the 20000 ones used in the former phases. This study is more exhaustively described in section 6.

The main metrics that have been used for the evaluation of the results of the project have been the spectral efficiency and the outage probability, which have been explained in section 3.1.7.

4. Analysis of the variations of different network configuration parameters

As mentioned in section 3.2, the first phase of the project consisted in performing different sets of simulations varying some of the parameters, and analysing the results in order to evaluate the impact that those changes have on the overall performance of the network.

The reference configuration for the simulations performed in each of the sections below is the one shown in table 3.3, and every parameter variation has been done independently for each section.

4.1. Changing the number of base stations

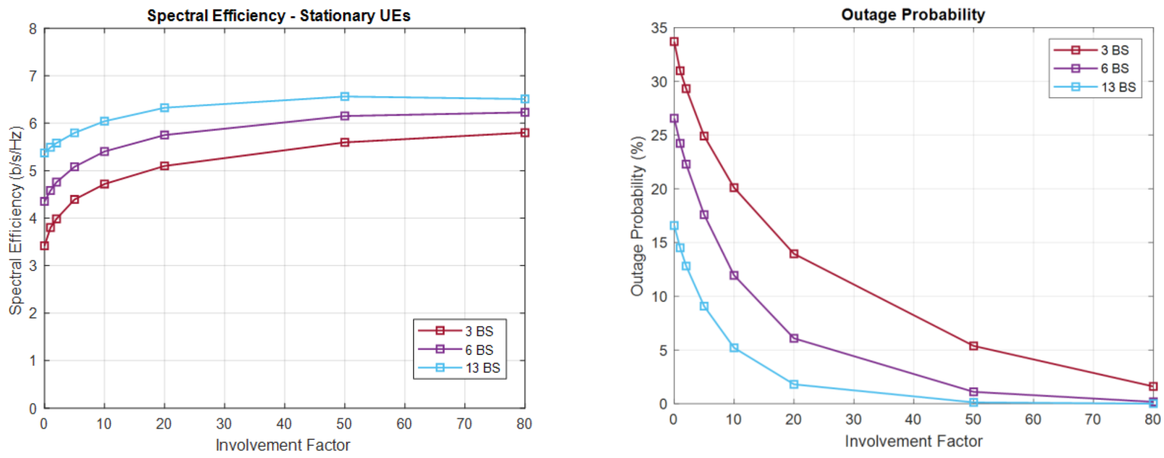
To begin with, a set of simulations has been performed choosing scenarios with different numbers of base stations present in the area. The different scenarios contained 3, 6 and 13 base stations. Then, the obtained results in terms of achieved spectral efficiency and outage probability have been analysed.

Figure 4.1 a) shows the average spectral efficiencies of the total of the users achieved with different amounts of relays for each of the three cases.

As it can be seen, the lower the number of base stations, the bigger is the improvement that the relays can introduce, so they become more useful. For example, we can see how with 3 base stations and 10% of the stationary UEs acting as relays (215 relays), the obtained average spectral efficiency is 38% higher than in the case where there are no relays. With this same amount of relays, the achieved improvements are 24.2% in the case of having 6 base stations and 12.4% with 13 base stations.

In addition, we can also see how with 3BSs and 10% relays we can achieve a higher spectral efficiency than the one in the case of 6BSs and no relays, which also happens in the 6BS and 13BS case.

A similar thing happens with the obtained outage probabilities. The figure 4.1 b) shows the values for stationary indoor UEs. The initial probability is higher when there are less base stations in the area, but the improvement introduced by the relays is much more significant.



a) b)

Figure 4.1: a) Spectral efficiencies and b) outage probabilities obtained varying the number of BSs

4.2. Variation of the transmission power of the BS

Another analysis that has been made is to perform simulations varying the transmission power of the base stations. We have performed sets of simulations with 13 BSs and the transmission power set to 15dBm, 25dBm and 35dBm.

The results have then been analysed in terms of the outage probabilities and the spectral efficiencies achieved by the UEs.

On the one hand, figure 4.2 shows the outage probabilities of the indoor stationary UEs, which are the kind of users that will most likely be found in an outage situation.

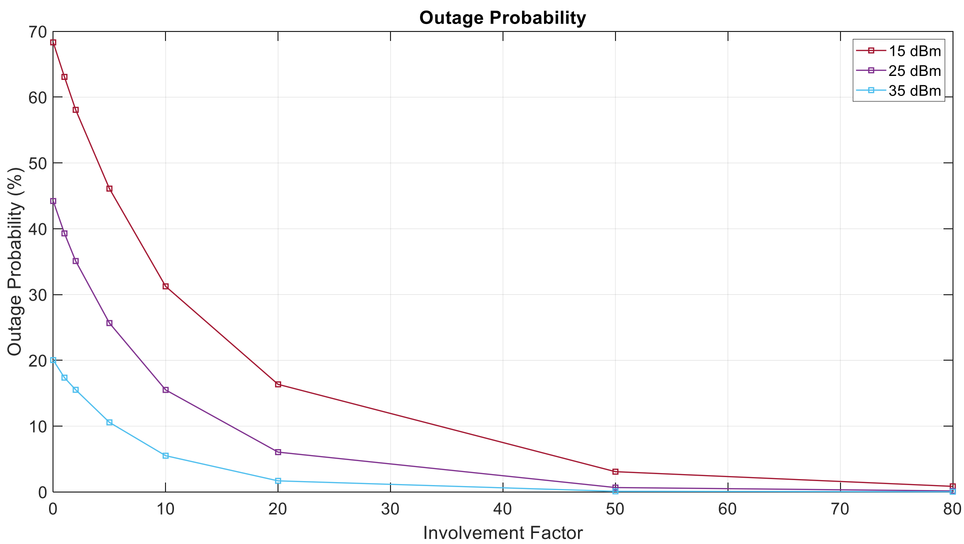


Figure 4.2: Outage probabilities of indoor stationary UEs when varying the BS transmission power

As it can be observed, the fact of introducing relays is extremely helpful to the network, to the extent that the obtained outage probability with an 80% involvement factor (1720 relays) is very similar in all three cases. In the case of having a transmission power of 15dBm, the outage probability is reduced from 68% with no relays to 0.85% with 80% of involvement factor. On the other hand, when the transmission power is 35dBm, the outage probability is reduced from 20% to 0.03%.

Besides, we can also check how, with the BSs transmitting at 15dBm but introducing 20% of the stationary UEs as relays (430 relays), we achieve a lower outage probability than when the BSs transmit at 35dBm.

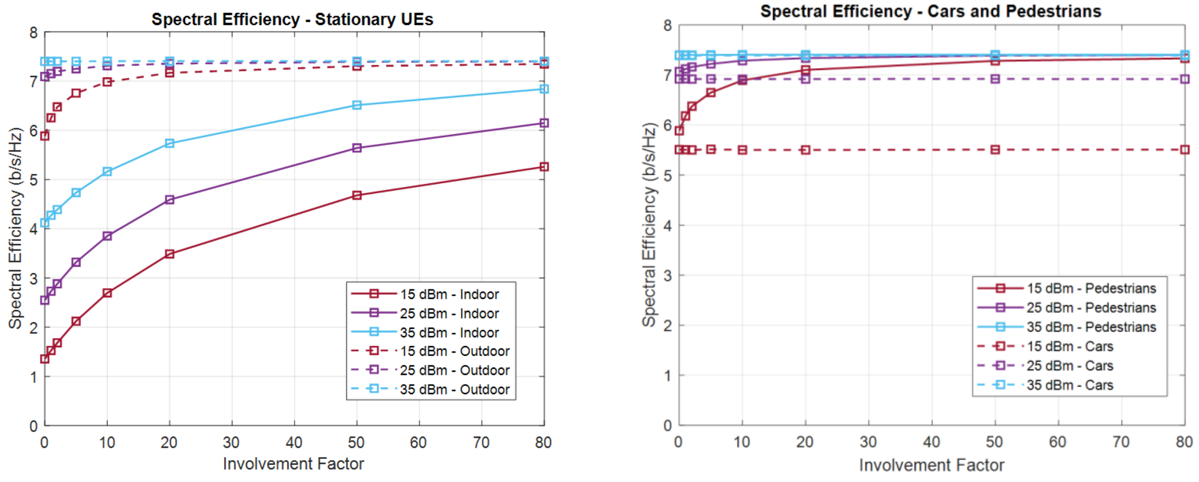
We may alternatively interpret the results checking that, in order to achieve an outage probability lower than 5%, an involvement factor slightly over 10% (215 relays) would be needed if the BSs transmitted at 35dBm, whereas, if they transmitted at 25dBm, the needed involvement factor would be of about 30%, and finally, with 15dBm the needed value would slightly lower than 50% (1075 relays).

This shows that the relays happen to be more useful when the power of the BSs is lower and thus, the indoor UEs suffer from worse conditions.

Figure 4.3 shows the spectral efficiencies of the indoor and the outdoor stationary UEs. We can observe how the outdoor UEs are the ones that benefit the most from the relays, as was the case with the outage probabilities. For the cases of 15, 25 and 35 dBm, the achieved increases are 287%, 141% and 65% respectively.

On the other hand, in the case of the outdoor UEs, the relays are mostly helpful when the transmission power of the BSs is lower, but even in this case, there is a point where the relays stop being helpful and the spectral efficiency remains the same even if the involvement factor increases. Furthermore, in the case of 35dBm, the spectral efficiency remains stable, regardless of the number of relays.

Additionally, we can analyse the spectral efficiencies of the pedestrians and the cars. We observe how the case of the pedestrians is very similar to the case of the outdoor stationary UEs explained before, where the relays only have an impact when the transmission power is lower. On the other hand, since cars never connect to relays, their spectral efficiency is constant and is not affected by the involvement factor. As a result of the change of the transmission power, this constant value will increase or decrease accordingly.



a) b)

Figure 4.3: Spectral efficiencies of stationary UEs (a) and cars and pedestrians (b) when varying the BS transmission power

4.3. Variation of the transmission power of the relay

The next analysis consists in performing simulations keeping the transmission power of the BS at 25dBm and varying the transmission power of the relays. Just as in the former case, we have performed sets of simulations with 13 BSs, setting the relay transmission power to 15dBm, 25 dBm and 35dBm.

In figure 4.4, we can analyse the outage probability of the indoor stationary UEs. As it can be observed, all three cases start on the same value when there are no relays. Then, the outage probability is reduced as the involvement factor grows, and this reduction is bigger when the transmission power is higher. However, we can see how when the involvement factor is high enough, all three cases end up being more similar, to the extent that with an 80% involvement factor the achieved outage probabilities are 1%, 0.15% and 0.08% for 15dBm, 25dBm and 35dBm respectively.

Another way of reading these results is that, in order to achieve an outage probability lower than 5%, an involvement factor slightly lower than 20% (430 relays) would be needed if the relays transmitted at 35dBm, whereas, if they transmitted at 25dBm, the needed involvement factor would be of about 30%, and finally, with 15dBm the needed value would be about 50% (1075 relays).

From these results it can be inferred that, when the number of relays present is lower, increasing the transmission power of the relays significantly improves the network's performance.

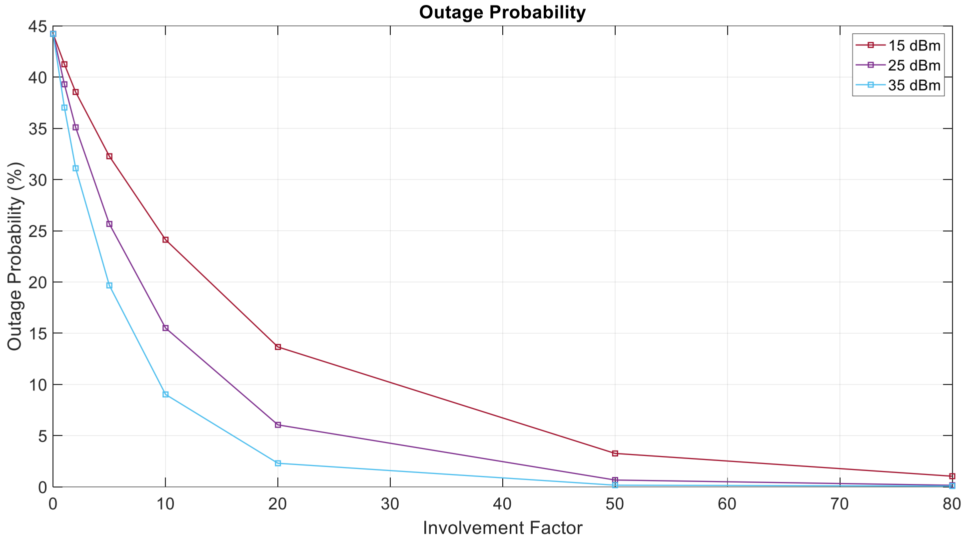


Figure 4.4: Outage probabilities of indoor stationary UEs when varying the relay transmission power

On the other hand, if we analyse the spectral efficiencies in this case, as shown in figure 4.5, we can see that the most significant improvement is observed by the indoor stationary UEs, in which case the spectral efficiency grows with the number of relays, and, the higher is the transmission power, the bigger is the obtained value.

For the outdoor stationary UEs and pedestrians, on the contrary, the relays only introduce a slight improvement and the results hardly vary with the transmission power.

Finally, the cars are not affected by this variation since they do not get connected to relays.

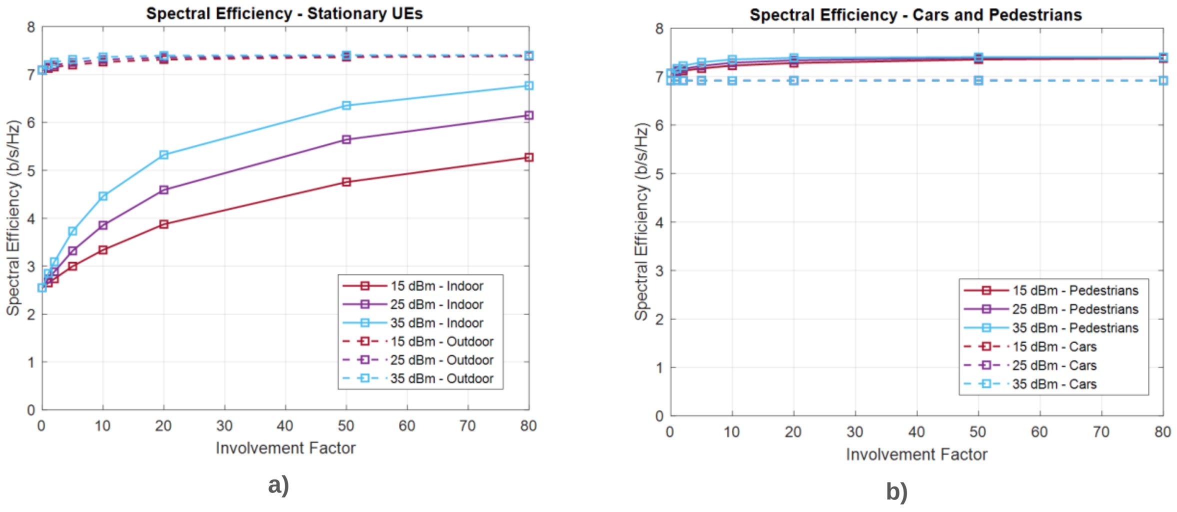


Figure 4.5: Spectral efficiencies of stationary UEs (a) and cars and pedestrians (b) when varying the relay transmission power

4.4. Variation of the BS frequency

Another analysis that was carried out involved the variation of the BS frequency from 26 GHz to a sub-6GHz frequency, which was set to 3.7 GHz.

In this case, the scenarios with and without beamforming were studied. In order to consider a scenario without beamforming, the antenna gains of the UE and the BS were reduced. The set values are shown in table 4.1:

BS	
Antenna Gain	10 dB
UE - Direct Link	
Antenna Gain	3 dB

Table 4.1: BS and UE antenna gains for the case without beamforming

First, we check the results obtained for the beamforming case. Figure 4.6 shows the outage probabilities obtained by the indoor stationary users and the average spectral efficiency values for both 26 GHz and 3.7 GHz cases with beamforming. We can see how the 3.7 GHz case provides higher spectral efficiencies and lower outage probabilities even at the case with no relays, given the better propagation conditions achieved through the lower frequency.

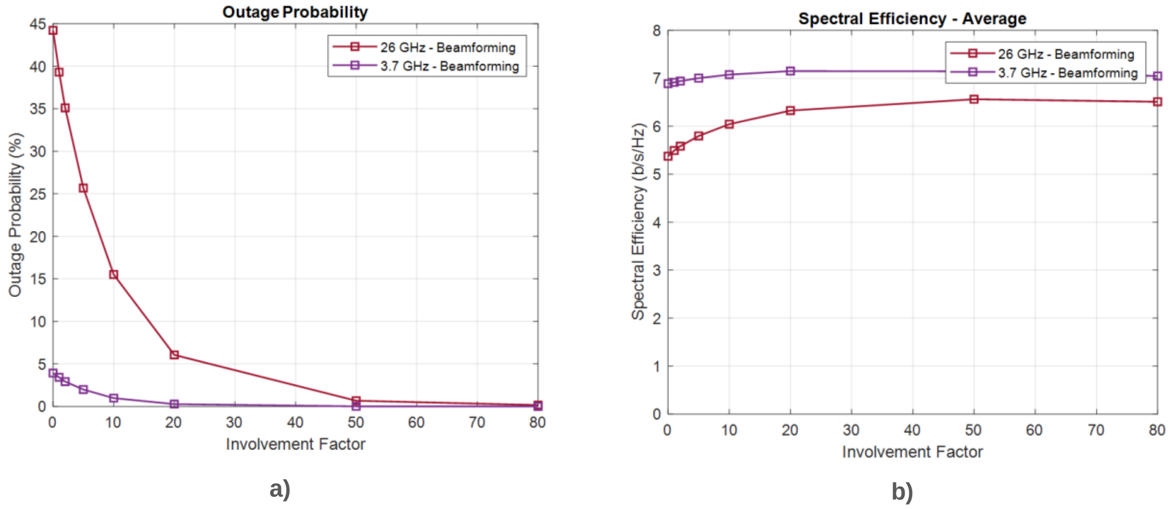


Figure 4.6: Outage probabilities of stationary UEs (a) and average spectral efficiencies (b) when varying the BS frequency with beamforming

This effect can also be observed very clearly looking at the spectral efficiency maps obtained in both cases at ground level and seventh floor level, shown in figure 4.7. From these results we can infer that the usage of relays is not very useful in the 3.7 GHz and beamforming case, since the initial results are already good and the improvement margin is quite small.

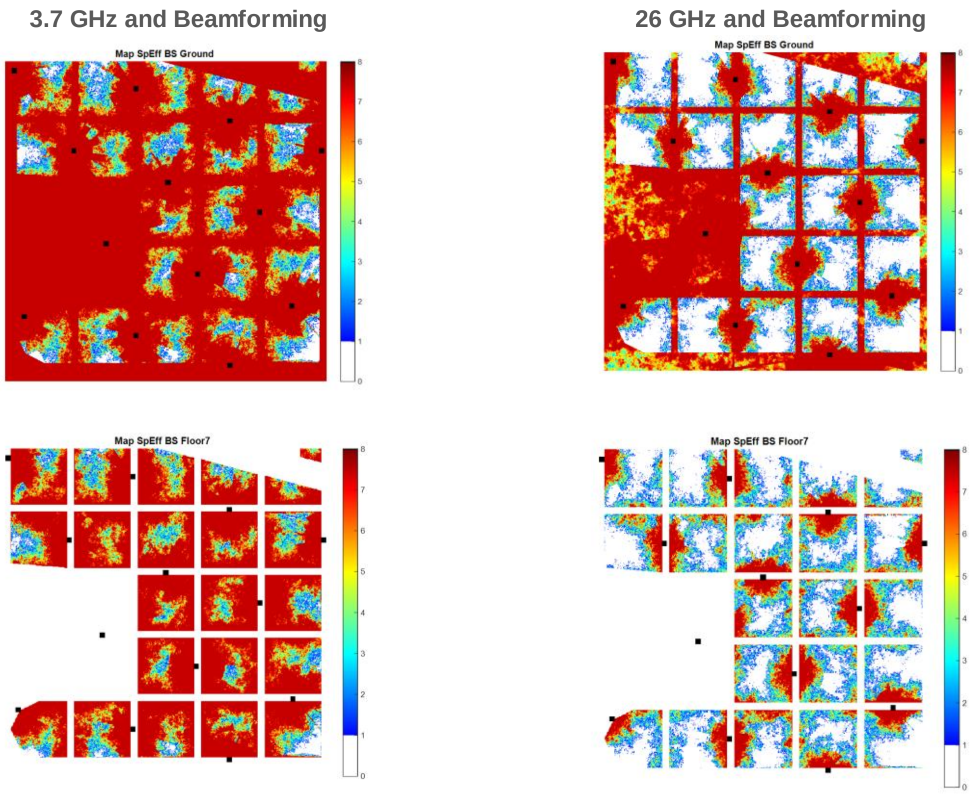
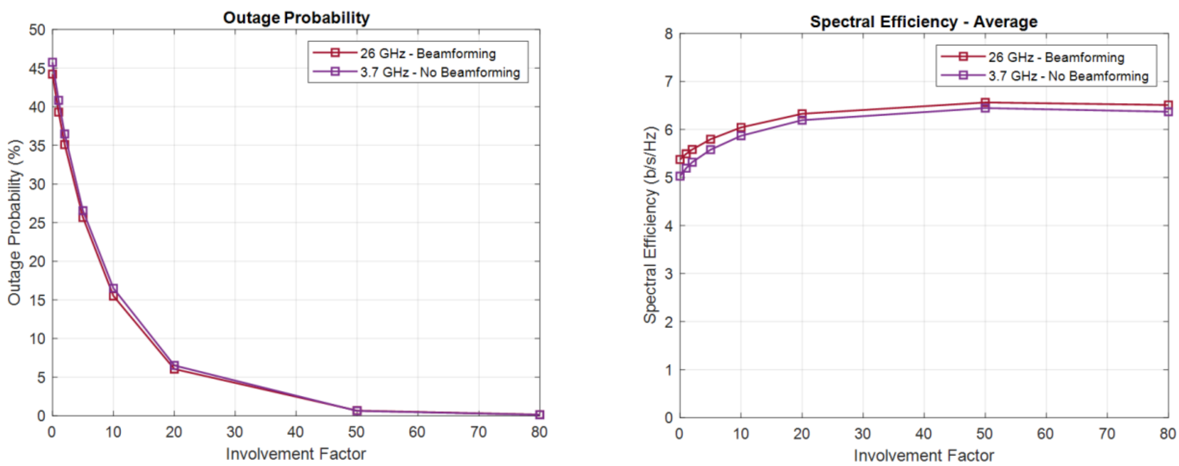


Figure 4.7: Spectral efficiency maps for 3.7 GHz case (left) end 26 GHz case (right) at the ground level (top) and 7th floor (bottom)

On the other hand, we analyse the scenario with 3.7 GHz and no beamforming. In this case, as it can be seen in figure 4.8, the obtained results both in spectral efficiency and in outage probability are very similar to the 26 GHz with beamforming case. Therefore, we can infer that relays are useful in this case, since they significantly reduce the outage probability of users and also increase the obtained spectral efficiency.



a) b)

Figure 4.8: Outage probabilities of stationary UEs (a) and average spectral efficiencies (b) when varying the BS frequency without beamforming

4.5. Allowing multi-hop

Finally, the effect of the multi-hop on the performance of the network was analysed. This means that the relay UEs can be connected to other relays instead of being directly connected to the BS, splitting the backhaul link in two or more independent links, as shown in figure 4.9.

Multihop relaying reduces the path loss between transmitter and receiver with the addition of intermediate wireless relays. Since the link hop is shorter, the path loss is greatly reduced, and obstacles can be avoided so that the SINR is increased and random signal fluctuations due to both shadowing and scattering are reduced. This allows obtaining higher link capacities and improved reliability. [18]

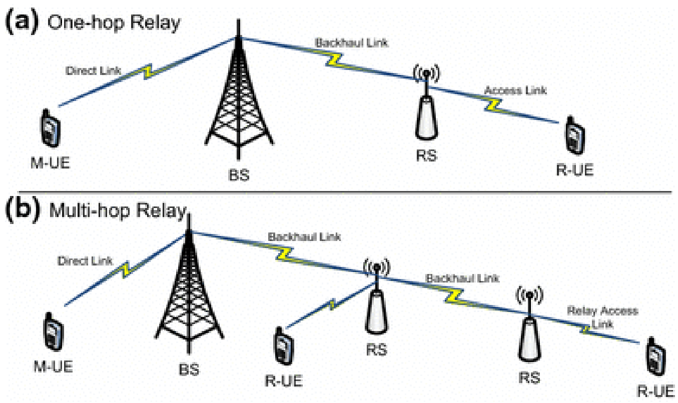


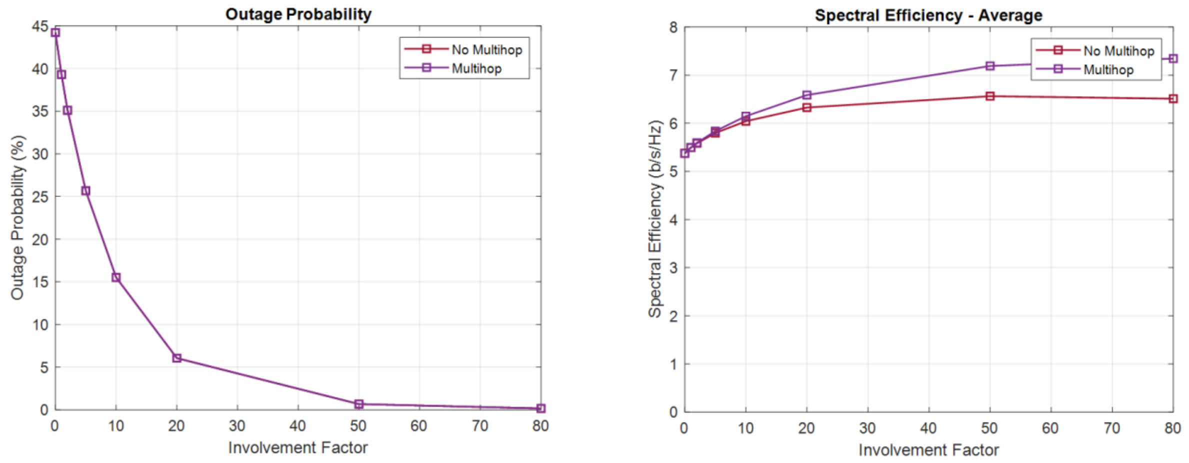
Figure 4.9: One-hop relaying vs. multi-hop relaying [19]

In this case, the configuration parameters are set back to the reference values specified in table 3.3.

As we can observe in figure 4.10 b) the observed total average spectral efficiency is higher in the case of allowing multihop, and the difference is higher when the number of active relays is bigger.

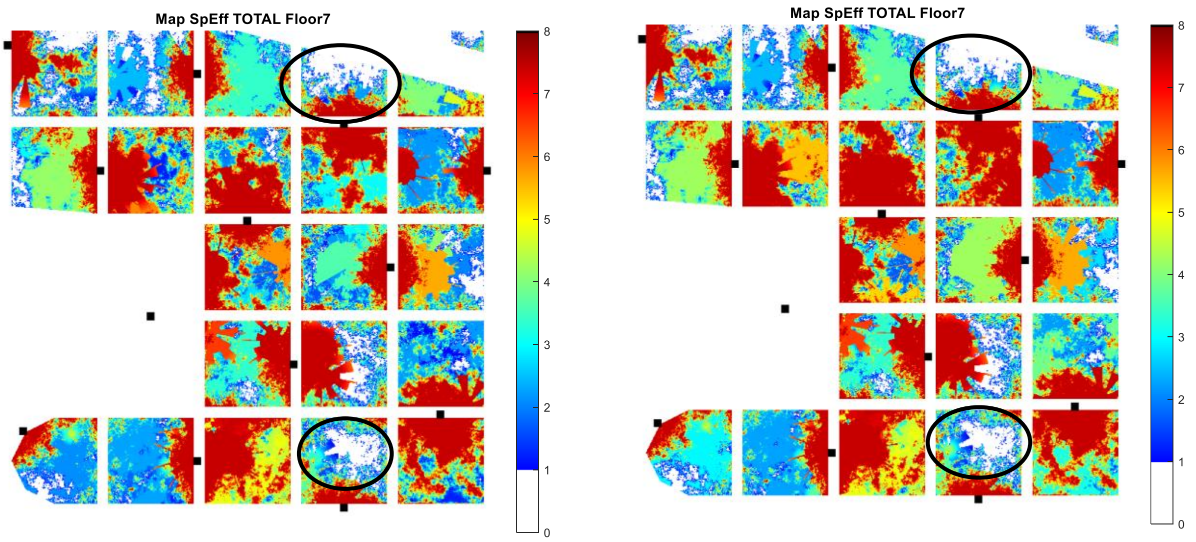
The outage probability of the indoor UEs (fig. 4.10 a), however, remains exactly the same when multihop is allowed. This can be explained due to the fact that, even if multihop allows the relay nodes to observe better conditions and therefore provide better spectral efficiencies to the users, the actual relays in the two cases are the same. This means that the range that the relays cover with or without multihop is the same as well, and the relay-UE link is not affected by the multi-hop. If we observe the spectral efficiency maps of the cases with and without multihop in figure 4.11, we see how some specific areas which were already covered in the case of no multihop improve their spectral efficiencies. The outage areas (white), however, remain the same in the two cases.

Therefore, we can conclude that multi-hop mainly allows the improvement of the BS-relay link, but not the relay-UE link, so the users that are in outage cannot benefit from it.



a) b)

Figure 4.10: Outage probabilities of stationary UEs (a) and average spectral efficiencies (b) with multihop



a) b)

Figure 4.11: Spectral efficiency map including BSs and relays for F=20, without multihop (a) and with multihop (b)

5. Relay Characterisation

As it has been mentioned in section 3, in order to analyse the performance of the UEs used as relays by evaluating the common characteristics of the ones that help the most and the least, we have enhanced the simulation code in order to count the number of users that are served by each of the relays and BSs at every moment of a simulation. Besides, in order to obtain more information about the performance enhancements introduced by the relays, we have as well counted the number of UEs served by the relay that were in outage with their serving BS, and we have identified the spectral efficiency improvement introduced by the relay for each user.

In this process we have taken into account the category to which those UEs belong, as well as if they are placed in an indoor or outdoor environment.

This network analysis procedure has been carried out by performing simulations for different configurations of available relays, varying the involvement factor as has been formerly explained. For each value of F, we perform 50 simulations, where each execution simulates 10000 seconds. That way, we perform simulations corresponding to analysing the network during 50000 seconds (138.8 hours) for each of the different configurations of available relays.

Once that process is over, we gather the results obtained in all simulations and we obtain a list of the 20000 relays which includes how many times those relays have appeared in a simulation, and the average values of the monitored criteria for all of those appearances.

- Criterion 1: Number of UEs served by the relay

Firstly, we perform the analysis of the relays which have a higher amount of UEs served by them. This value is obtained by computing the average number of users served by a relay during a whole simulation process, and then, if that same relay has appeared in more than one simulation out of the different executions, the average number of served UEs is averaged again considering all the appearances of that given relay. This way, we obtain a single value of the average UEs served by a relay.

- Criterion 2: Introduced spectral efficiency improvement

In order to be able to evaluate how helpful a relay actually is to the users around it, we have also taken the approach of analysing the spectral efficiency improvement introduced by each relay to the UEs that are connected to it.

This value was firstly obtained by computing the ratio between the spectral efficiency offered by the relay to a given user and the spectral efficiency that the user would obtain if it was connected to the base station.

$$Spectral\ Efficiency\ Improvement = \frac{S\,eff_{relay}}{S\,eff_{BS}}$$

In order to avoid the division by zero, when the spectral efficiency offered by the BS is null, we set its value to 0.01 b/s/Hz, which is below the minimum value set in the simulations (0.2344 b/s/Hz).

However, it was seen that this solution introduced great distortion in the resulting values (as it will be explained later), so the way to obtain this spectral efficiency improvement was changed, making it the difference between the spectral efficiency offered by the relay to a given user and the spectral efficiency offered by the base station:

$$Spectral\ Efficiency\ Improvement = S\,eff_{relay} - S\,eff_{BS}$$

At the end of each simulation, the average spectral efficiency improvement is obtained for each relay, and, finally, the results are averaged again taking into account all the simulations of each of the F values. This way we obtain an average spectral efficiency improvement value for each of the 20000 relays.

- Number of UEs served by the relay that were in outage with their serving BS

Finally, in order to keep evaluating the usefulness of a relay to the UEs around it, we have analysed the number of users served by a relay that would be in outage in terms of the spectral efficiency offered by the BS, and are now out of outage thanks to the spectral efficiency offered by the relay.

This value is acquired based on the process of obtaining the number of connections of each relay. When a UE is added to the count of a relay, we check the spectral efficiencies available in the position of that user both with and without taking the relays into account. If the spectral efficiency was below the outage limit set for the simulations (1b/s/Hz) without the relays and is over it with them, the counter of outage users goes up.

At the end of the executions, we proceed the same way as with the counting of the total number of users, averaging this value at each simulation and then averaging it again in case it has appeared in more than one simulation.

5.1. Analysis of the results

5.1.1. Relay Appearances

It needs to be taken into account that, since the available relays are selected randomly from the database, the number of times that each relay appears in a simulation is different. The following graph shows the histogram of the relay appearances in the total of 350 simulations.

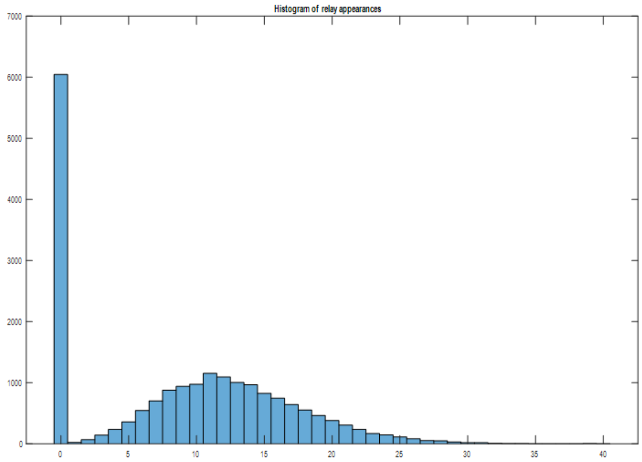


Figure 5.1: Histogram of the relay appearances

As it can be seen, there are about 6000 relays that never even appear on the simulation, so our practical database actually has 14000 relays. The main reason why most of these relays never appear is because their assigned positions are in outage and therefore invalid positions, so they are never selected. Then the number of appearances vary from 22 relays that appear only once to one relay that appears 40 times. The distribution is approximately normal, where the most common number of appearances is 11 with 1153 relays.

5.1.2. Impact of the considered criterion

Once we have associated all three criteria to the 20000 relays of the database, we obtain the 50 relays with the highest value for each case, in order to analyse them.

On the one hand, we can study the positions of those relays by showing them in the map. The yellow squares represent the base stations, and the smaller squares represent the 50 selected relays. The number shown on the right of each relay corresponds to the identification number of that relay in the 20000 relays database. Besides, the colour of each of the small squares represents the floor they are placed at.

- Analysis of the relays based on the number of UEs served by a relay

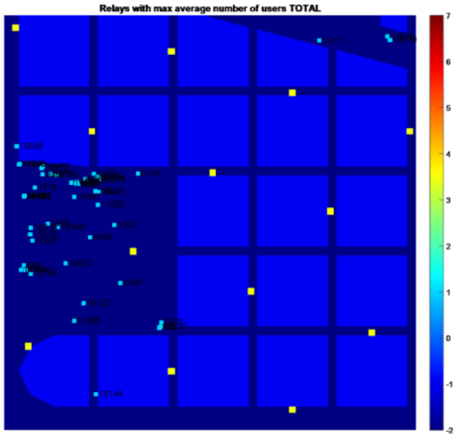


Figure 5.2: Positions of relays with maximum number of connected UEs

Observing the map shown in figure 5.2, we can see that the relays with the highest number of served users are the ones located in the area of the Joan Miró square and that all of them are in floor 1, which represents the street level.

These results are logical considering that, in the simulations, all the area has the same user density, but, in the case of the buildings, that density is divided among the seven floors. This means that the street areas have seven times more user density than the building floors. However, the fact of having more UEs connected to them does not mean that those relays offer the best conditions improvement to the users located in those areas. In fact, if we observe the map of the spectral efficiencies offered by the base stations in the street area (figure 5.3) we can see that the values around Joan Miró square are very high, which means that the users would not have suffered from bad conditions had they not connected to a relay.

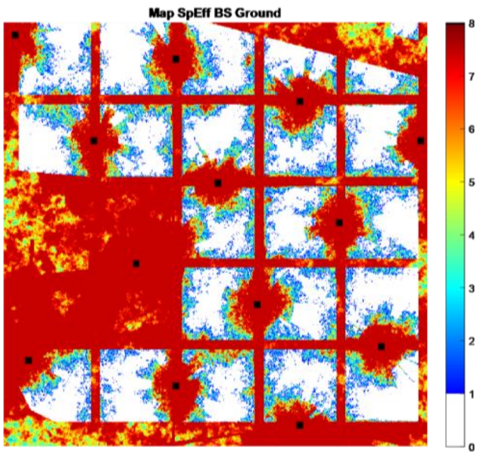


Figure 5.3: Map of the spectral efficiencies offered by BS in ground floor

- <u>Analysis of the relays based on the introduced spectral efficiency improvement</u>

Checking the results obtained through the computation of the ratio between spectral efficiencies, we obtain the following relays as top ones:

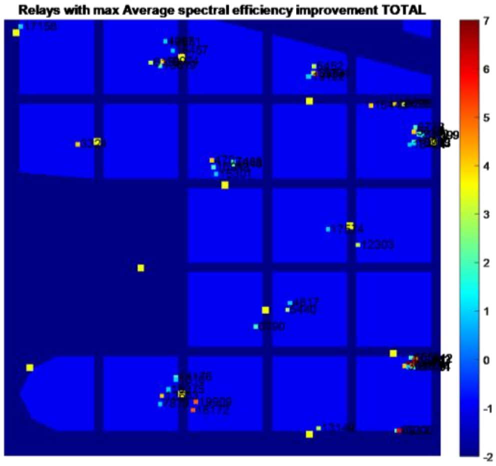


Figure 5.4: Positions of relays with maximum offered spectral efficiency improvement (ratio)

As it can be seen, the relays tend to be placed in indoor locations, where the spectral efficiency offered by the base stations is worse due to propagation conditions; but they are still quite close to the BSs, since, in order to offer adequate conditions, they need to have good connections themselves. The higher spectral efficiencies obtained in locations close to the BSs can be seen in figure 5.5.

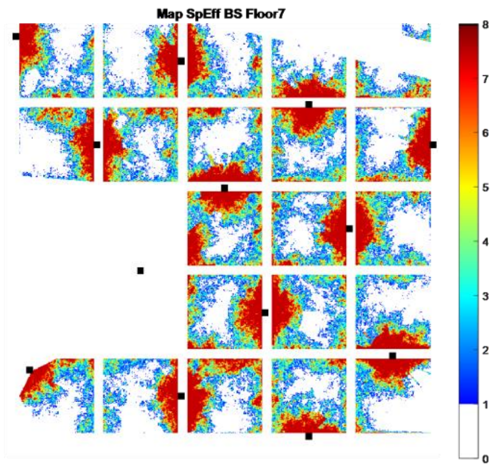


Figure 5.5: Map of the spectral efficiency offered by the BSs in floor 7

On the other hand, if we check the results obtained by computing the difference between the spectral efficiencies, we get the following top 50 relays:

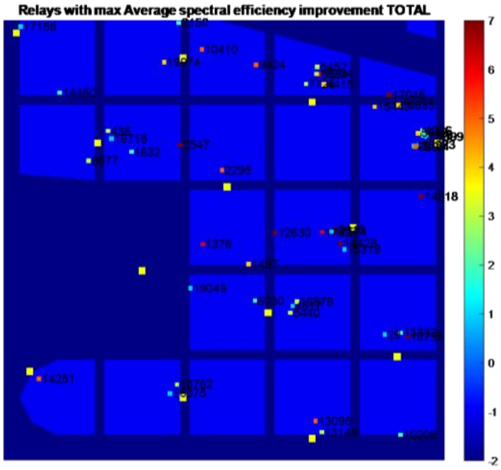


Figure 5.6: Positions of relays with maximum spectral efficiency improvement (difference)

It can be seen that the top relays are not the same as in the former case, but they follow a similar tendency, since they are located in interior areas and close to the base stations, but they are slightly more spread out.

- <u>Analysis of the relays based on the number of UEs served by the relay that were in outage with their serving BS</u>

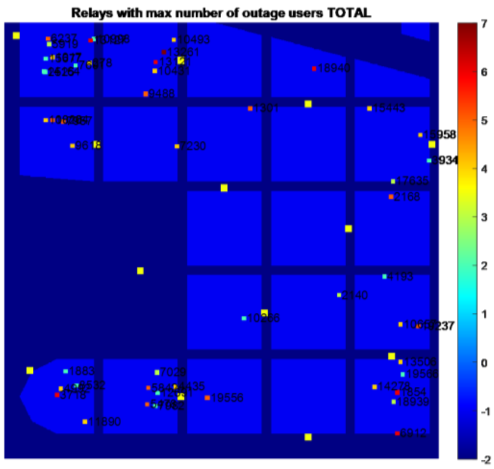


Figure 5.7: Positions of relays with maximum number of users in outage

In this case, we can also see how the relays that provide better results are located in interior areas, where, just like in the former case, the spectral efficiency offered by the base stations is worse. However, it can also be observed that there is a tendency for those relays to be located towards the edges of the simulation area.

If we continue analysing the top 50 relays of each of the three cases by looking at quantitative data, it is useful to cross check the obtained values between them for the top 50 relays of each criterion.

- Number of UEs served by a relay

Having the top 50 relays of the first criterion, we check the average values they take:

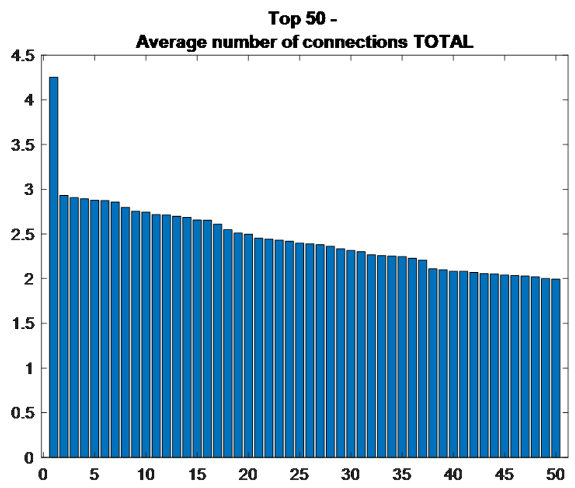


Figure 5.8: Average number of users served by the top 50 relays of the first criterion

Analysing those maximum values, we can see that the majority of the relays have an average connection value of between 1.9 and 3 users per simulation.

However, if we analyse the spectral efficiency improvement values of those top relays (computed through the difference), we see that the maximum difference they offer is 1.8 b/s/Hz, and most of them offer under 1 b/s/Hz, while, as we will see in the next section, relays can offer a difference of over 6 b/s/Hz. Besides, we see that many of these relays have a spectral efficiency difference of around 0, which means that the spectral efficiency achieved is very similar with and without the relay.

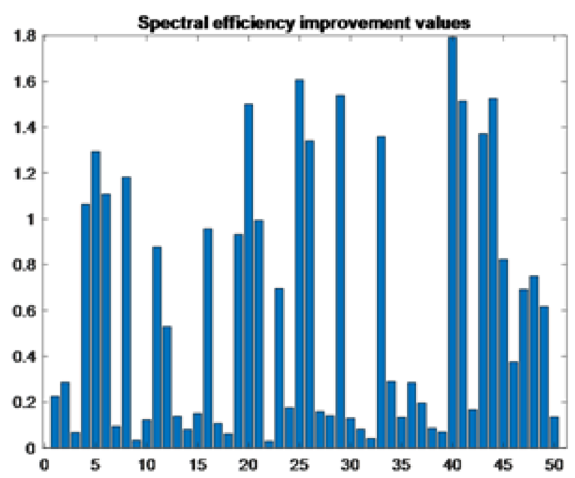


Figure 5.9: Average spectral efficiency improvement of top 50 relays of the first criterion

Moreover, checking the average number of users in outage that are served by these relays, we see that the values are mainly under 0.05 users on average, so they are not being very helpful to the users around them.

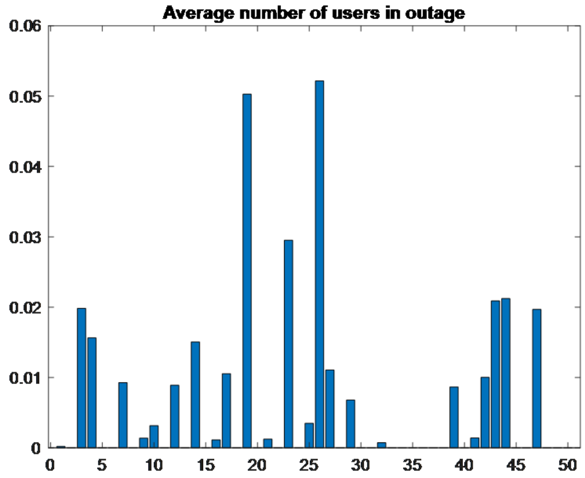


Figure 5.10: Average number of users in outage of top 50 relays of the first criterion

These results show how the relays that have the highest amounts of average served UEs actually do not bring a significant improvement to the users around them.

- <u>Introduced spectral efficiency improvement</u>

Next, we analyse quantitative values of the top 50 relays of the second criterion.

First, we check the average improvement values that were achieved when computing them by performing the ratio. As it can be seen, due to the introduction of the division by 0.01 in order to avoid the division by zero, we see that the relays take values of around 400, with the highest ones arriving at 550. These values, however, are not very illustrative given that they suffer from distortion.

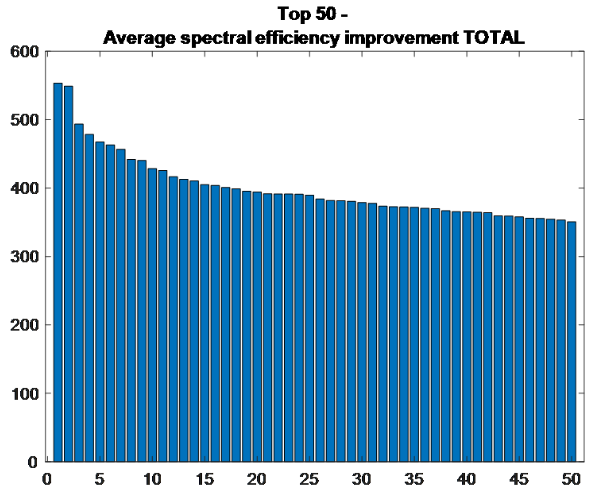


Figure 5.11: Average spectral efficiency improvement (ratio) of top 50 relays of the second criterion

Looking at the values obtained by computing the difference between spectral efficiencies, on the other hand, we see clearer values. It can be seen how the top 50 relays achieve to offer over 5 b/s/Hz more to the users when comparing it with the spectral efficiency offered by the base stations.

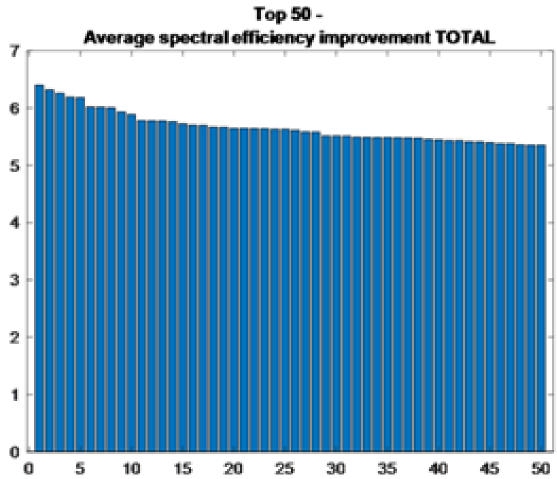


Figure 5.12: Average spectral efficiency improvement (difference) of top 50 relays of the second criterion

On the other hand, looking at the average numbers of served UEs that these relays achieve, we can appreciate that the values are quite low, with most of them being under 0.5 users.

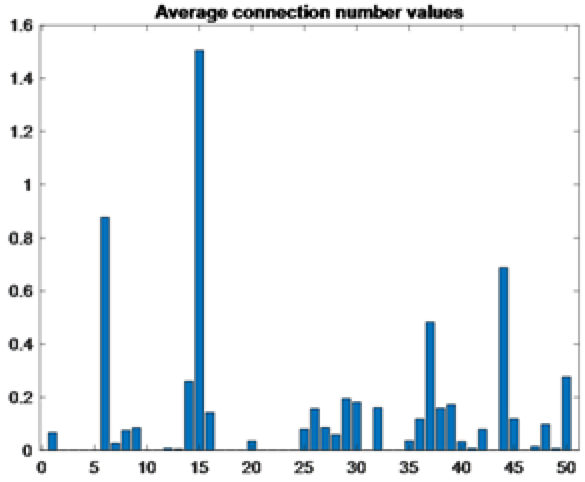


Figure 5.13: Average number of users served by the top 50 relays of the second criterion

Besides, the values of the average number of users in outage served by those 50 relays can be seen in the next graph, where we see that, even if the average number of connections are lower, the number of users in outage are higher, which means these relays prove to be more helpful to the network, since they save more users from the outage situation.

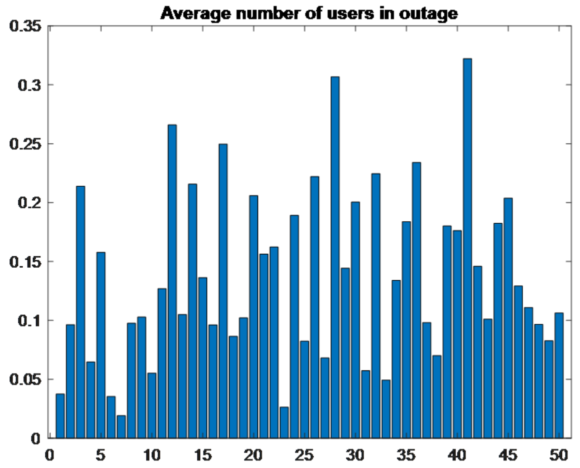


Figure 5.14: Average number of users in outage of top 50 relays of the second criterion

- <u>Number of UEs served by the relay that were in outage with their serving BS</u>

Finally, analysing the values obtained by the top 50 relays of the third criterion, we obtain the following graph:

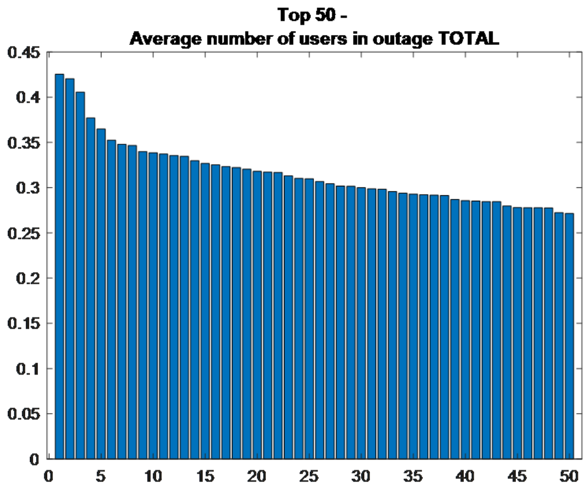


Figure 5.15: Average number of users in outage of top 50 relays of the third criterion

It can be seen that they reach an average of around 0.3 users, with a few of them reaching over 0.4.

When it comes to the spectral efficiency improvement values, we appreciate that they vary a lot, and they are not necessarily the highest ones.

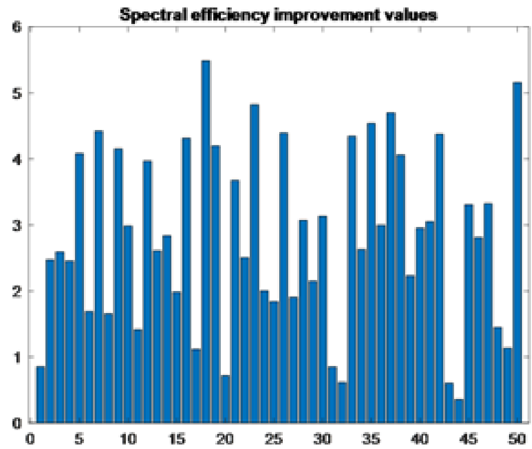


Figure 5.16: Average spectral efficiency improvement of top 50 relays of the third criterion

The average number of served UEs, on the other hand, is seen to be quite low, showing once again that the most helpful relays are not the ones that get more users connected to them.

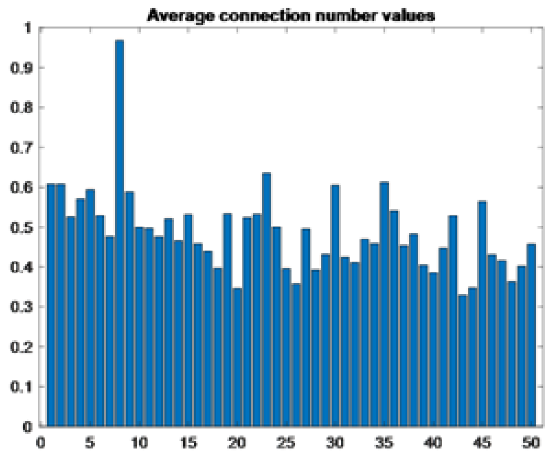


Figure 5.17: Average number of users served by the top 50 relays of the third criterion

5.2. Application of the obtained results for relay selection

Once we obtained and analysed the results of the simulations, a strategy has been developed which defines how to use these results in order to improve the network.

The main idea is to create a ranking of the relays according to one criterion out of the three available ones. Since we want the relays to be as helpful to the network as possible, the criterion chosen to build the ranking has been the number of users in outage. This way, we obtain a list of the 20000 relays, ordered from the ones that get more connections in outage to the ones that get less.

With this ranking built, we have taken two different approaches to use it in the simulations.

5.2.1. First approach - Simple case

On the one hand, we consider a simple case in which we carry out a set of simulations (50 simulations for each value of involvement factor explained before) where all the relays selected are directly taken from the top of the ranking. This way, we obtain the results of an ideal case where all the relays present in the simulation are the most useful ones.

The graph in figure 5.18 shows the comparison between the outage probabilities obtained between the case where the relays are selected randomly (dotted line) and the case with the relays of the top of the ranking (continuous line). The orange lines represent the stationary UE located indoors, which are the only category of UE that suffer from outage. The blue lines represent all the stationary UEs (indoor and outdoor). These last ones are lower but proportional, since they are compensated by the null outage probabilities of the outdoor stationary UEs.

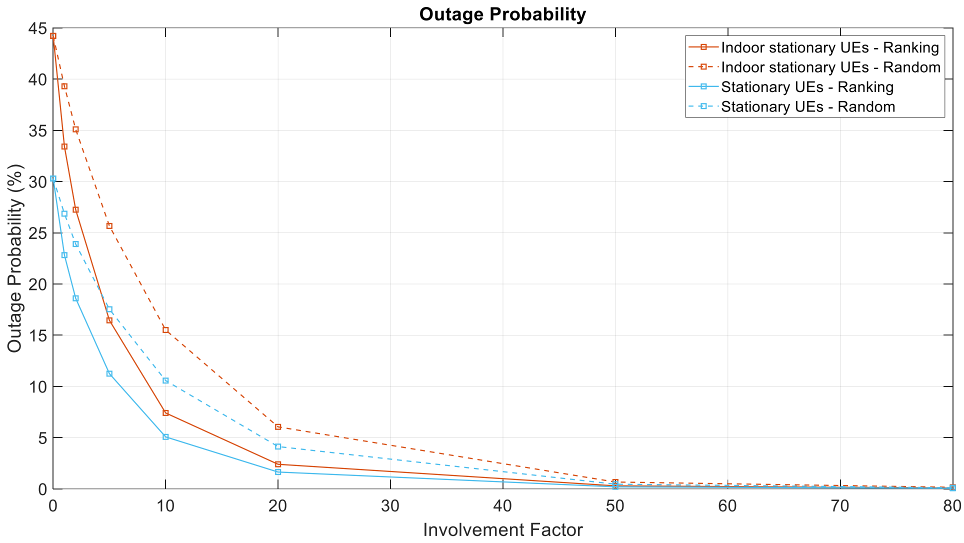


Figure 5.18: Outage probabilities of random relays (dotted line) and ranking relays (continuous line).

As it can be seen, the selection of the top relays causes a great improvement in the outage probabilities, making them decrease significantly. This difference is bigger with lower values of involvement factors (F=5, 10 or 20). For example, in the case of F=10, the outage probability decreases from a 15% to a 7.5% when selecting the top relays. Besides, we can check how when we set F=10 and select the top relays, we achieve a very similar outage probability to the one in the case of having double the relays (F=20) but with a random selection.

However, for bigger values the difference is not as significant, because, given that the number of relays is higher, a random selection of relays can also ensure a sufficient amount of relays that are useful to the network or located in indoors areas.

Figure 5.19, on the other hand, shows the comparison between the spectral efficiencies obtained in this case. The green line represents outdoor UEs, the orange line represents the indoor ones and the blue line represents the total. As in the former case, the dotted line corresponds to the random selection case and the continuous line corresponds to the case where the top relays of the ranking are selected.

We see how the offered spectral efficiency increases when using the top relays in the ranking in the case of indoor areas, where it achieves an increment of 25% in the case of F=20. However, the spectral efficiency is slightly reduced for the case of outdoor UEs. This result is logical given that the top relays of the ranking tend to be located in indoor areas.

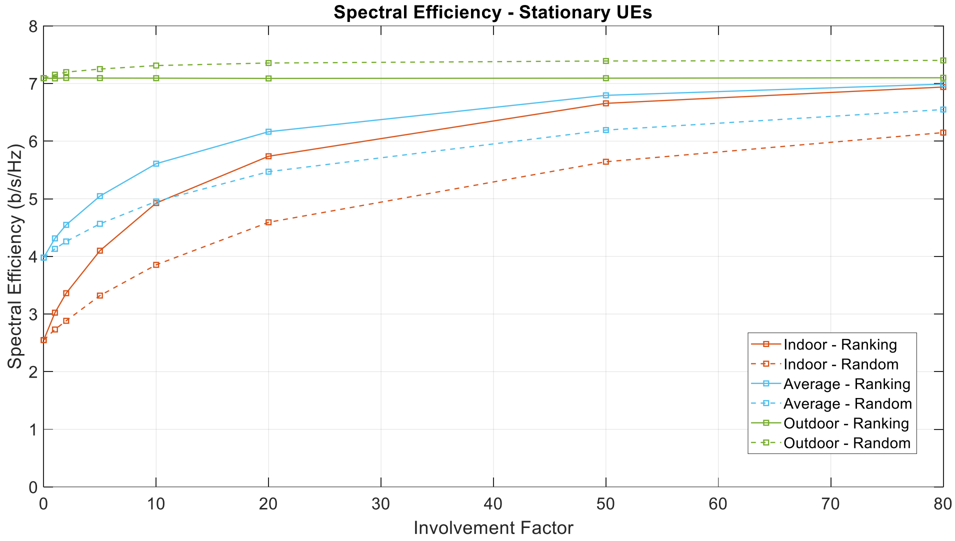


Figure 5.19: Spectral efficiencies of random relays (dotted line) and ranking relays (continuous line).

5.2.2. Second approach - Practical case

On the other hand, we have carried out a more practical case in which we have introduced a new variable N, which corresponds to the number of relays that are activated out of the total available relays for each value of F. The relays that will be activated are selected according to the ranking position of the available relays, choosing the N highest ones.

We have performed simulations for different values of F, making N vary from 10 to 800.

Figure 5.20 shows the obtained outage probabilities of the indoor stationary non-relay UEs. Each continuous line corresponds to the results obtained for a given value of F, and the X-axis corresponds to the number of relays that were active for each set of simulations (N). The green dotted line indicates the minimum achievable outage probability for that value of F, which is the one obtained when all the available relays are active. Also, the circular marker specifies the maximum number of relays for each value of F.

Checking the results, we can see that for the highest values of F, with a significantly lower number of relays, we can obtain results very close to the ones obtained activating all the available relays. For example, for F = 20, with N = 250 an outage probability of 6.43% is achieved, where, with all 420 relays activated, it takes a value of 6.05%. Also, for F = 80, with N=800 relays the outage probability is 0.23% and with all 1720 relays it is 0.15%.

Besides, we can see how with F=50 and F=80, the outage probabilities obtained are very similar. This is due to the fact that, when a big number of relays are available, the number of “unuseful” relays also grows, and these do not contribute to lowering the outage probability. Putting it in another way, the best 400 relays out of 1075 or out of 1720 are likely to introduce similar improvements.

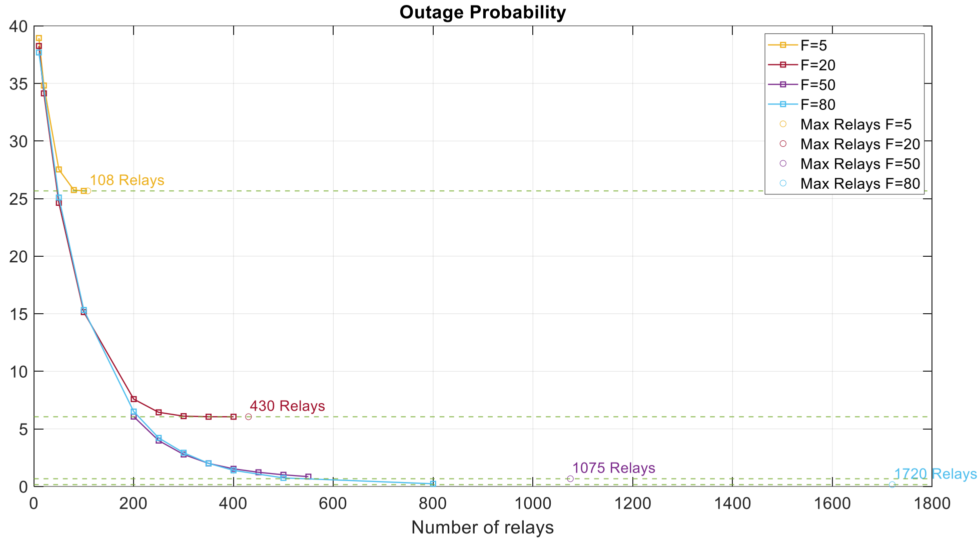


Figure 5.20: Outage probabilities of indoor stationary non-relay UEs for F=5, F=20, F=50 and F=80

Checking the total outage probability (taking into account all user types) values shown in figure 5.21, we see how it follows the same tendency, but the probabilities are lower since they are compensated by user types with null outage probability.

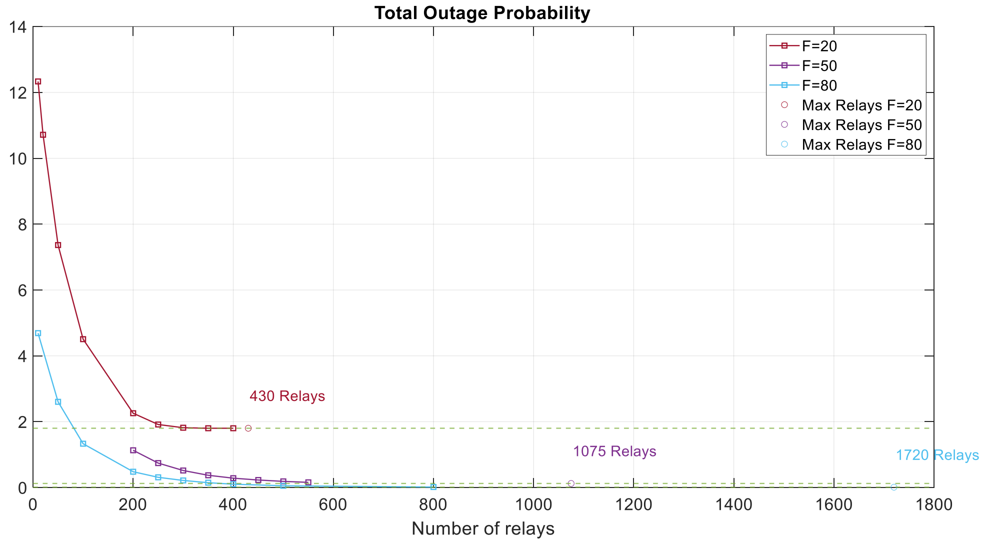


Figure 5.21: Total outage probabilities for F=20, F=50 and F=80

A similar thing happens with the spectral efficiency, shown in figure 5.22, where values close to the optimal result are achieved with a significantly lower number of relays. However, the closeness between results is not as big as in the outage probability case because the relays have not been ranked according to this criterion.

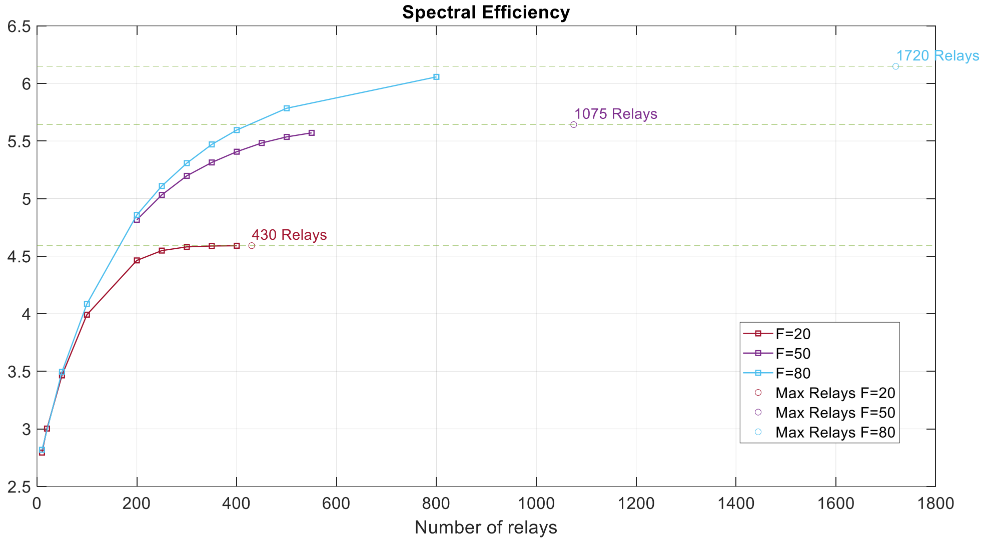


Figure 5.22: Average spectral efficiencies for F=20, F=50 and F=80

5.3. 6 Base Stations Case

An equivalent analysis has been performed for the case of the 6 Base Station scenario in order to evaluate the differences between the top relays of the three criteria in the two cases (13BS and 6BS), and check if the obtained results and conclusions are extrapolable to scenarios with lower number of BSs. The process of monitoring the formerly explained criteria per each relay has been carried out again, and the top 50 relays of each criterion have been analysed.

The following figure shows the positions of the top 50 relays of each criterion. As it can be seen, the results are analogous to the 13BS case. On the one hand, the relays with maximum number of served UEs are located outdoors and in the area of the square, due to the higher user density. On the other hand, the relays that offer the biggest spectral efficiency improvement are located in indoor areas and close to the base stations. Finally, the relays that serve the maximum number of UEs that would be in outage with their serving BS are also located in indoor areas.

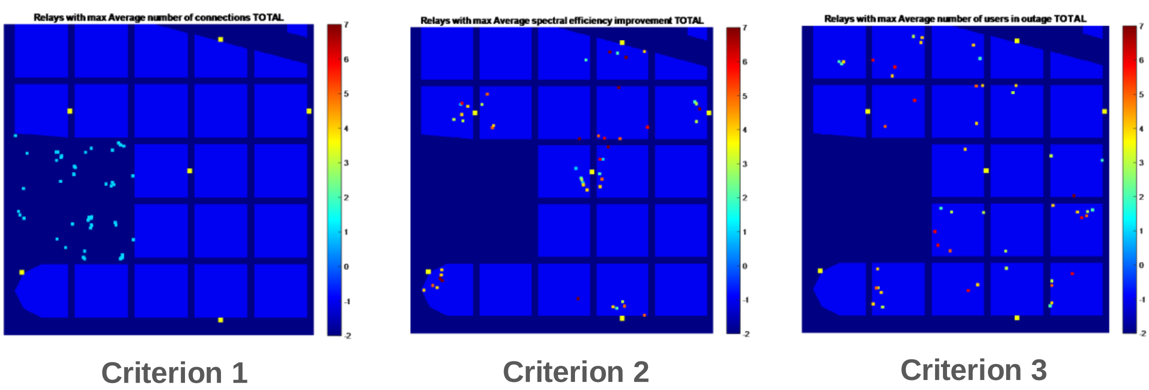


Figure 5.23: Positions of top 50 relays according to each criterion

When performing the quantitative analysis of the relays, we can see that the values of each of the three criteria follow the same tendency as in the 13BS case. However, since there are less base stations, the relays become more useful and the achieved values are higher.

The following figures show the analysed values for the top 50 relays of each criterion.

- Top 50 relays with maximum number of served UEs:

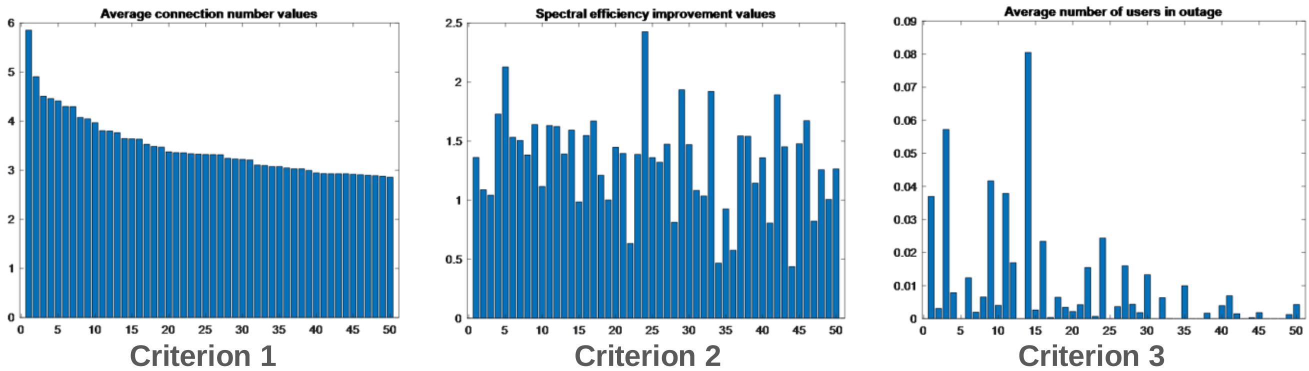


Figure 5.24: Values of top 50 relays of the criterion 1

Observing the top 50 relays of criterion 1, we see how the obtained values for the average number of users served is higher (reaching up to over 5 users), since the number of serving BSs is lower and more UEs get connected to relays.

The spectral efficiency improvement introduced by those relays is also remarkably higher, being over 1 b/s/Hz in most of the cases, while in the 13BS case there were many relays under 0.2 b/s/Hz.

The values of criterion 3, however, although slightly higher than in the 13BS case, are still very low, showing that the top relays of criterion 1 are not the most helpful to the network.

- Top 50 relays with maximum spectral efficiency improvement values:

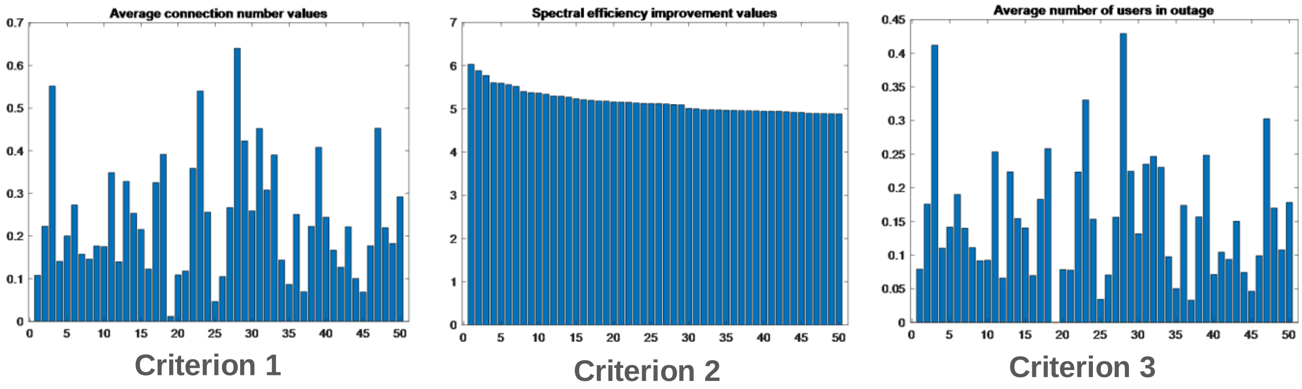


Figure 5.25: Values of top 50 relays of criterion 2

Checking the values of the top 50 relays of the second criterion, on the other hand, we see that they are slightly higher regarding criteria 1 and 3. The introduced spectral efficiency improvement values, however, are lower but still very similar, being almost always over 5 b/s/Hz.

However, we can still see how relays introducing the highest spectral efficiency improvement are not necessarily the ones that save more UEs from the outage, although they do better than top relays of criterion 1.

- Top 50 relays with maximum number of users in outage:

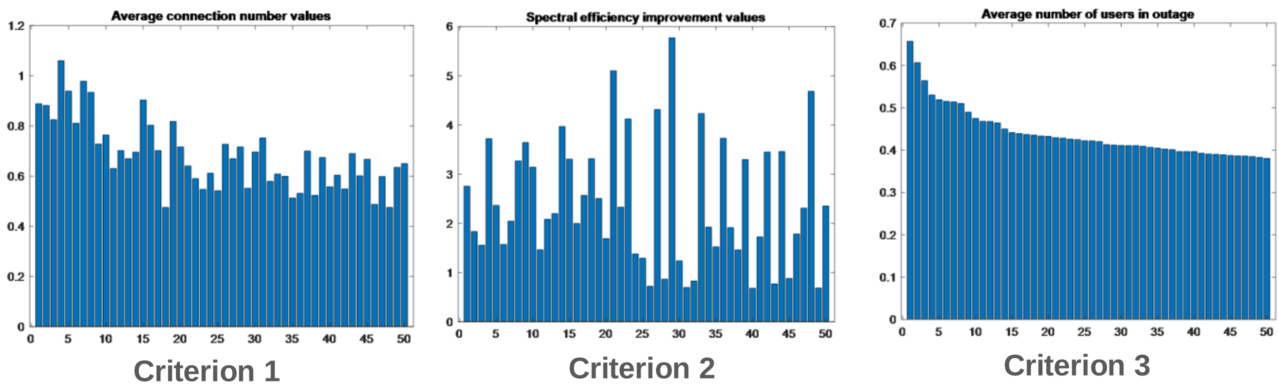


Figure 5.26: Values of top 50 relays of criterion 3

Finally, regarding the values obtained for the top relays of the third criterion, we can see that they are higher in all cases. The number of users in outage served by the relays goes up to being over 0.4 for all relays and reaching up to over 0.6, as opposed to the values with 13 BSs, that were around 0.3 average users.

The values of the introduced spectral efficiency are very similar to the 13BSs case, but the values of the number of users served by those relays (criterion 1) are also higher, showing again that in the 6BSs case the users are more likely to be connected to relays.

6. Relay activation approach exploiting a Network Digital Twin

The following phase of the project consisted in linking the idea of the relay ranking with the concept of the digital twin of the network, in order to devise a more practical applicability of the considered methodology.

In this approach, we consider a scenario in which a Network Digital Twin, which contains the exact same relay positions and features as the real network, characterises the available relays. This information will then be passed to the SMO platform of the real network in order to create the relay ranking, so that the obtained results can be applied to it, by means of activating the relays that have the highest positions in the ranking.

Besides, the system considers various timeframes with different spatial traffic distribution and different relay databases associated with each of them, so a different ranking is generated for every timeframe.

Here, the relay database was reduced from 20000 relays to 4300 relays, which corresponds to a more realistic scenario given that the total number of users considered in the simulator is 4300. These 4300 relays were ensured to be valid, meaning that they needed to observe a spectral efficiency higher than 1 b/s/Hz so that they would be able to offer good enough conditions to the users connected to them.

Figure 6.1 shows the overall scheme of the system.

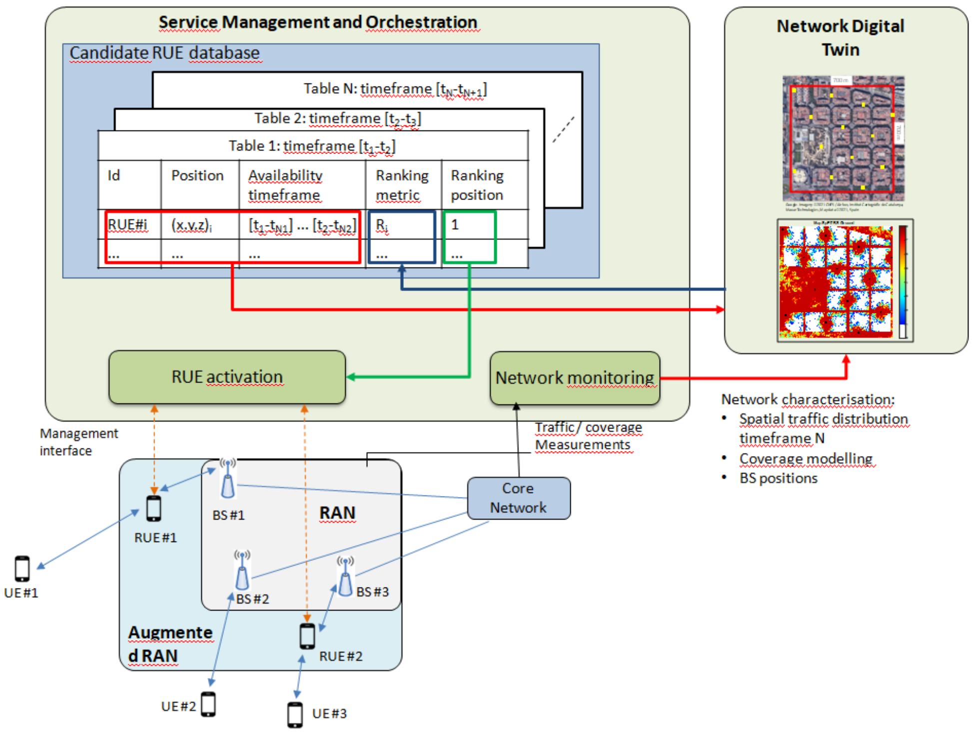


Figure 6.1: Scheme of the described system

Within this scenario, the relay characterisation was first performed, corresponding to the network digital twin side. The process slightly differed from the one explained in section 5. The relays were characterised according to the same three parameters explained before (number of users, spectral efficiency improvement and number of users in outage). However, the simulations did not have a fixed number of relays. Instead, a probability *p* was set and applied to each relay, so with probability *p* the relay would be active and with probability (1-*p*) the relay would be inactive. This way the number of active relays is different in each simulation, but the mean number of relays remains controlled.

Following this approach, simulation sets were carried out for four different values of *p*: 0.05, 0.1, 0.2, and 0.3, corresponding to means of 215, 430, 860 and 1290 relays respectively. This time, each simulation set consisted of 200 simulations of 10000 seconds. This was selected to ensure that each of the relays of the database had at least 100 appearances in this characterisation phase. After the relays were characterised, the ranking was created just as in section 5, according to the obtained number of users in outage.

Next, the simulations that recreate the real network were performed, applying the obtained relay ranking. In this case, two different variables were set: the total number of available relays (N_ava) and the number of relays that are activated out of those available (N). N_ava was given three different values (500, 1000 and 1500) and N was varied for each of the values of N_ava. Sets of 50 simulations were performed for each combination of N_ava and N, where in each simulation a different set of N_ava relays were randomly selected out of the database, and then activating the top N relays out of the available ones according to the obtained ranking. These results were then compared to the ones obtained when activating N random relays out of the available ones.

6.1. Timeframe 1

The first analysed timeframe considers a traffic distribution simulating a working day, in which the users are more likely to be outside their homes. The number of users in this case is a fixed value for each category:

Total	4300 Users
Pedestrians	1720
Stationary UE - Non Relay	1720
Cars	430

Table 6.1: Number of users per category in timeframe 1

This scenario considers a uniform distribution of users in the 2 dimensions of the map, but when it comes to stationary UEs, it does not consider a uniform distribution across floors, so the positions at each floor are less likely than the outdoor positions.

Furthermore, this scenario assumes that relays do not generate traffic of their own.

The reduced 4300 relay database in this case was created choosing the relays from the already existing 20000 relay database, selecting them out of the set of relays that had already appeared on the rest of the simulations performed, in order to ensure that they were valid and were not in outage positions. Besides, the relays were chosen in such a way that 90% of the relays would be in indoor positions.

- Results:

Figures 6.2, 6.3 and 6.4 show the comparison of the outage probabilities of indoor stationary UEs and the total outage probabilities obtained by activating the top relays of the ranking (continuous lines) or activating the relays randomly (dotted lines), for the cases of 500, 1000 and 1500 relays available.

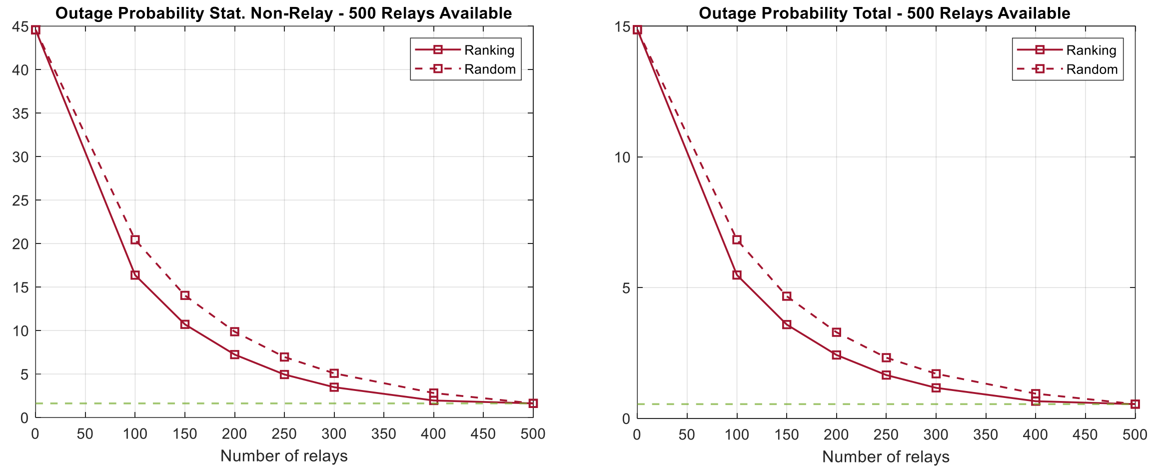
As it can be seen, the activation of the top N relays of the ranking introduces a significant improvement, especially in terms of outage probability. This difference is higher when the number of active relays is lower, because the relay selection has a bigger impact in this case.

For example, in the case of activating 100 relays, the outage probability of the indoor stationary non-relays is reduced from about 20% to 16% in all three cases, which corresponds to a reduction of the 20%; while when activating 250 relays, the outage probability is lowered from around 7% to 5%, which can be translated into a reduction of the 28%. This reduction percentages are very similar in the case of the total outage probability, even though the overall values are smaller, given the lack of outage situations for the rest of the user types.

Furthermore, it needs to be mentioned that the outage probability goes down from 45% in the case of not having any relays to 16% with 100 active relays. This means that a reduction of 66% is achieved in terms of outage probability for the indoor stationary non-relay users. In the case of the random activation, however, the outage probability decreases by 53%.

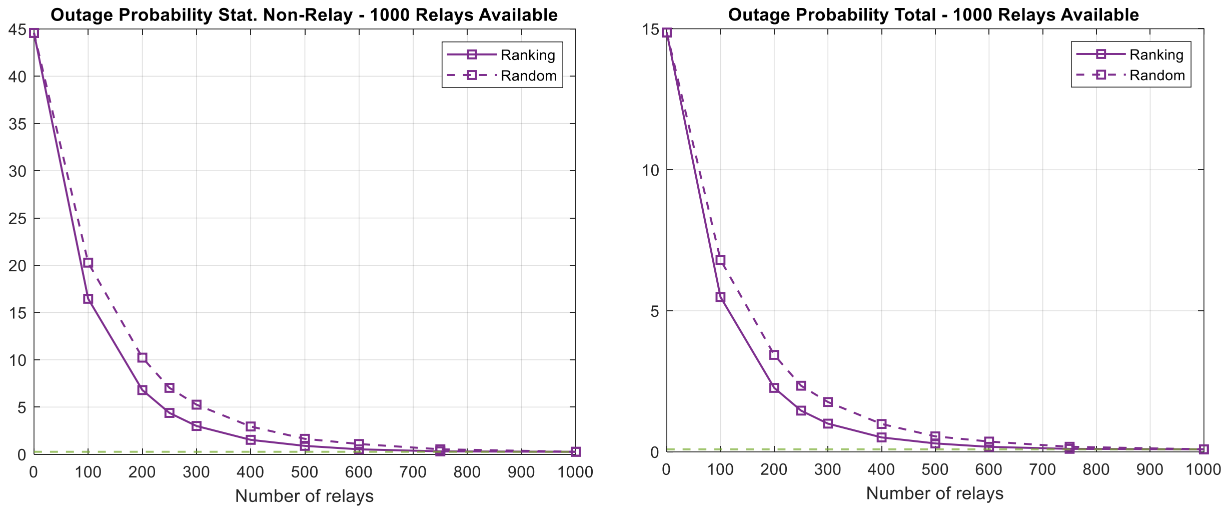
On the other hand, when the number of active relays is higher, the impact of selecting the top relays of the ranking is lower because the random selection already takes most of the top relays.

Besides, we can see how in order to achieve an outage probability lower than 5% for the indoor stationary users, we would need 250 relays when selecting them according to the ranking, while if they were selected randomly the needed amount of relays would be 300. This result applies for the three cases (500, 1000 and 1500 relays available) as well.



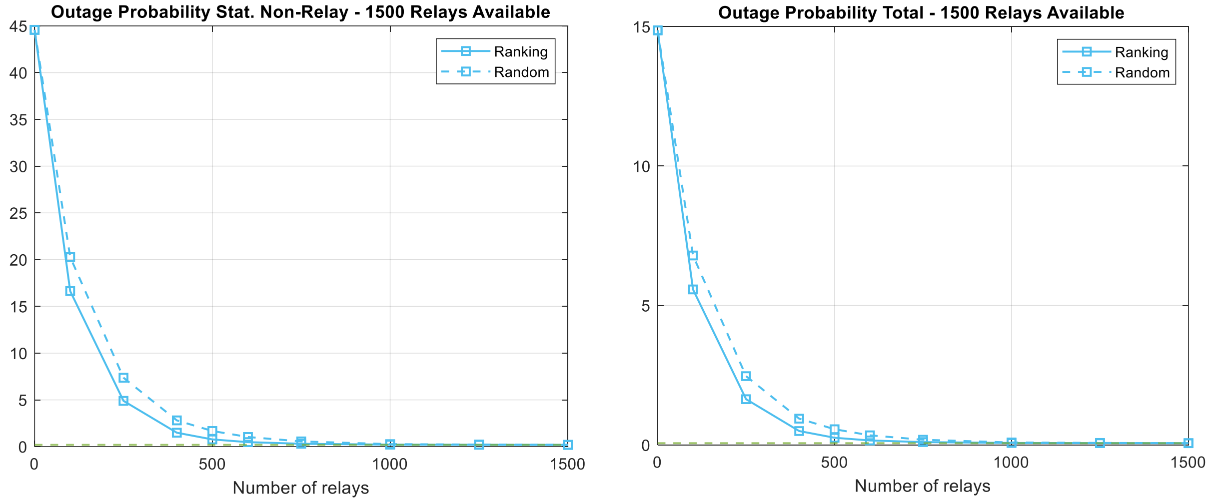
a) b)

Figure 6.2: Outage probability values of indoor stationary non-relays (a) and total (b) with 500 available relays in timeframe 1



a) b)

Figure 6.3: Outage probability values of indoor stationary non-relays (a) and total (b) with 1000 available relays in timeframe 1



a) b)

Figure 6.4: Outage probability values of indoor stationary non-relays (a) and total (b) with 1500 available relays in timeframe 1

Figures 6.5, 6.6 and 6.7, on the other hand, show the comparison of the same two cases but for the spectral efficiency values, also in the cases of the indoor stationary non relays and the total average for all user categories.

Regarding spectral efficiency, the relay selection according to the ranking also introduces some improvements, especially for the indoor users. In the case of activating 100 relays, the selection according to the ranking makes the spectral efficiency of indoor stationary users around 20% higher than the random case in all three cases, while the total value grows around 4%. When activating 250 relays, the spectral efficiency grows by 14%, 21% and 23% for the indoor stationary UEs for 500, 1000 and 1500 available relays respectively, while the total growth percentages are 2.5%, 4% and 4.5%.

In addition, we see that the activation of 100 relays based on the ranking causes an increase of 75% in the indoor stationary users when compared to the case of no relays, while the random activation brings an increase of 40%.

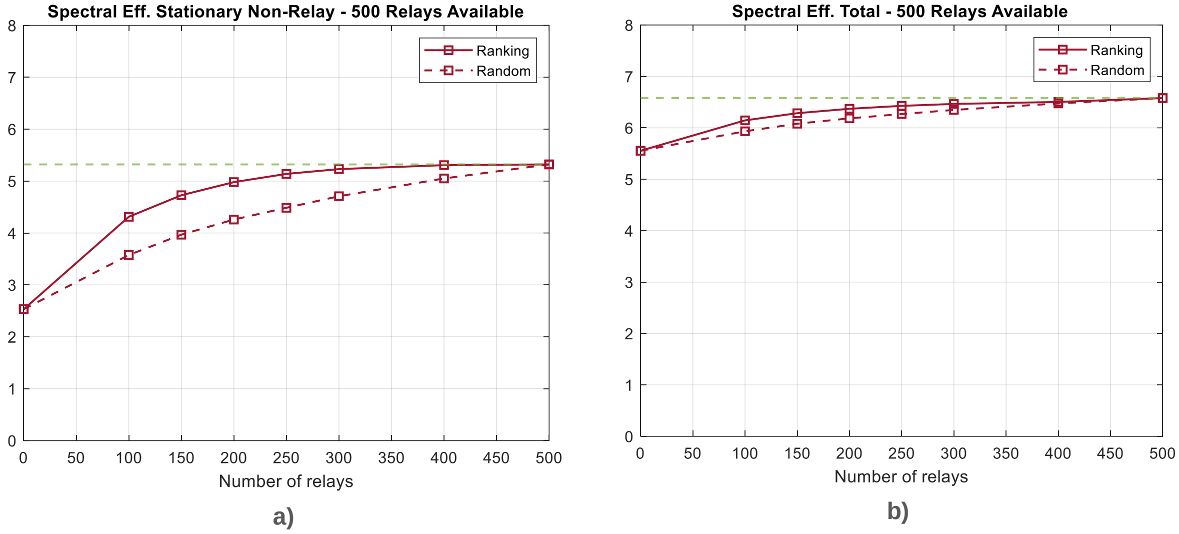


Figure 6.5: Spectral efficiency values of indoor stationary non-relays (a) and total (b) with 500 available relays in timeframe 1

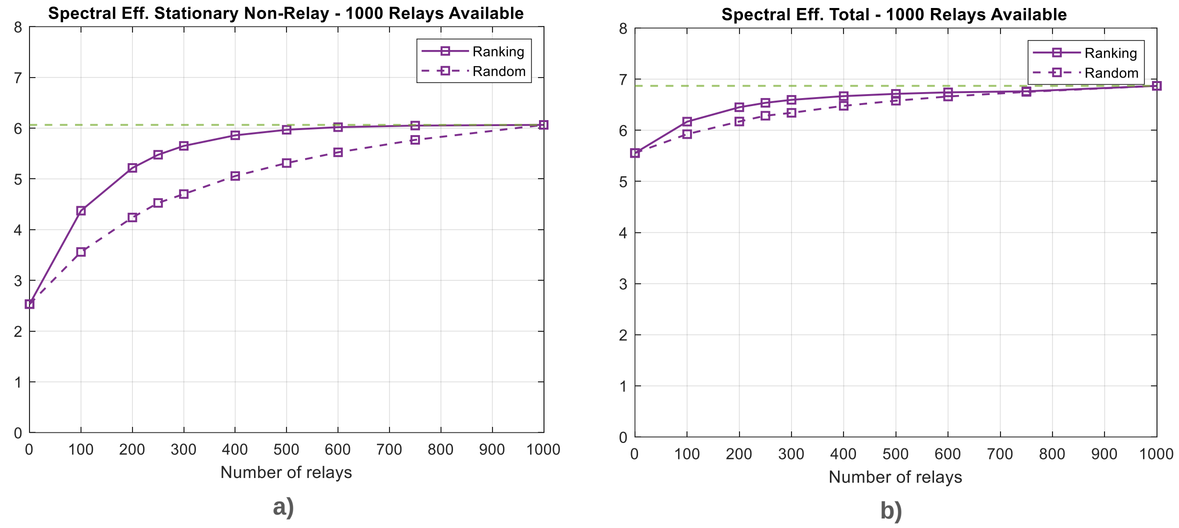


Figure 6.6: Spectral efficiency values of indoor stationary non-relays (a) and total (b) with 1000 available relays in timeframe 1

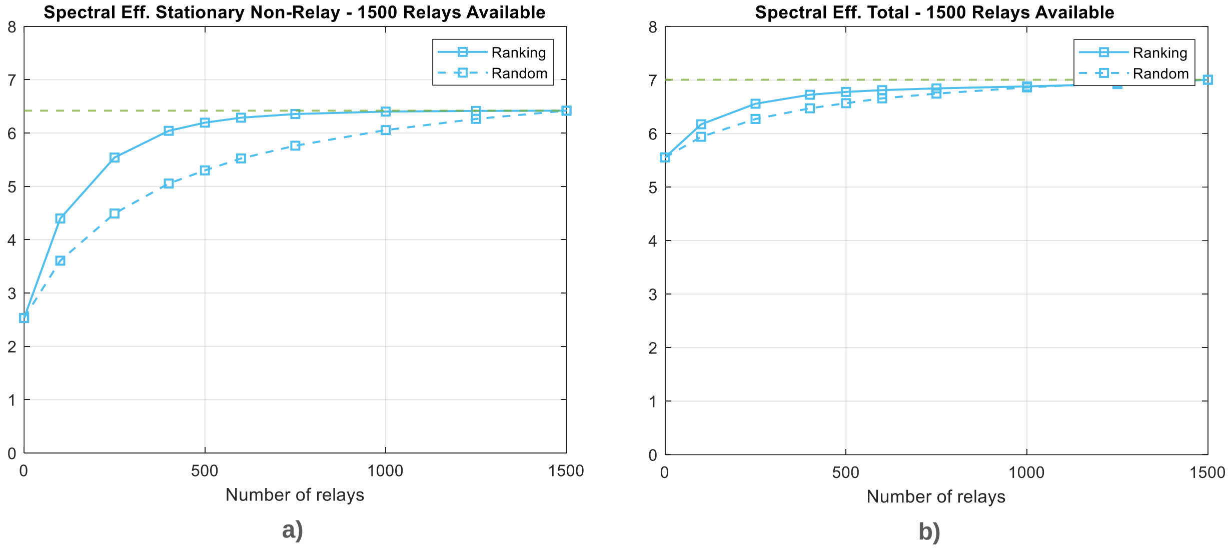


Figure 6.7: Spectral efficiency values of indoor stationary non-relays (a) and total (b) with 1500 available relays in timeframe 1

6.2. Timeframe 2

The second analysed timeframe, on the other hand, considers a scenario of the evening or night time of a working day, in which case users have a higher probability of being at home. The number of users in this case takes different values:

Total	4300 Users
Pedestrians	600
Stationary UE - Non Relay	2840
Cars	430

Table 6.2: Number of users per category in timeframe 2

In this scenario, the distribution of stationary UEs has also been modified in order to achieve a uniform distribution across floors, in the 3 dimensions. This has been done by forcing a higher probability of being indoors for the stationary UEs, which is specifically set to 7/8, given that the buildings are 7 floors high. This way, the probability of being on each floor is the same as the probability of being outdoors, which will be 1/8.

Furthermore, the relay database in this scenario is also a different one. This time the database was created from scratch, generating 4300 new relays with different associated positions and propagations to the already existing ones. These relays were created forcing the probability of being indoors to 7/8 as well.

- Results:

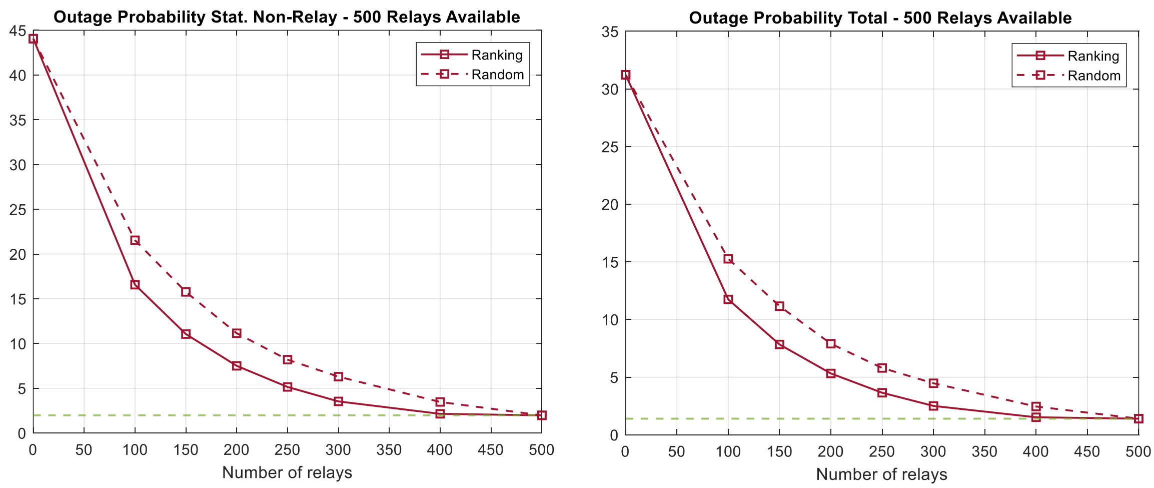
Figures 6.8, 6.9 and 6.10 show the comparison of the outage probabilities of indoor stationary UEs and the total outage probabilities obtained by activating the top relays of the ranking (continuous lines) or activating the relays randomly (dotted lines), for the cases of 500, 1000 and 1500 relays available.

We can see how the outage probability of the stationary indoor users with 100 active relays is reduced from about 22% with random selection to around 15% when using the ranking positions, which corresponds to a reduction of the 31%.

Furthermore, when activating 250 relays, the outage probability of indoor users is reduced from around 8% to 5% in the three cases, translating into a decrease of 37%. Besides, in order to obtain an outage probability lower than 5%, we can see that we would need 250 relays with the ranking selection, while, with the random selection the needed amount would this time be around 350 relays.

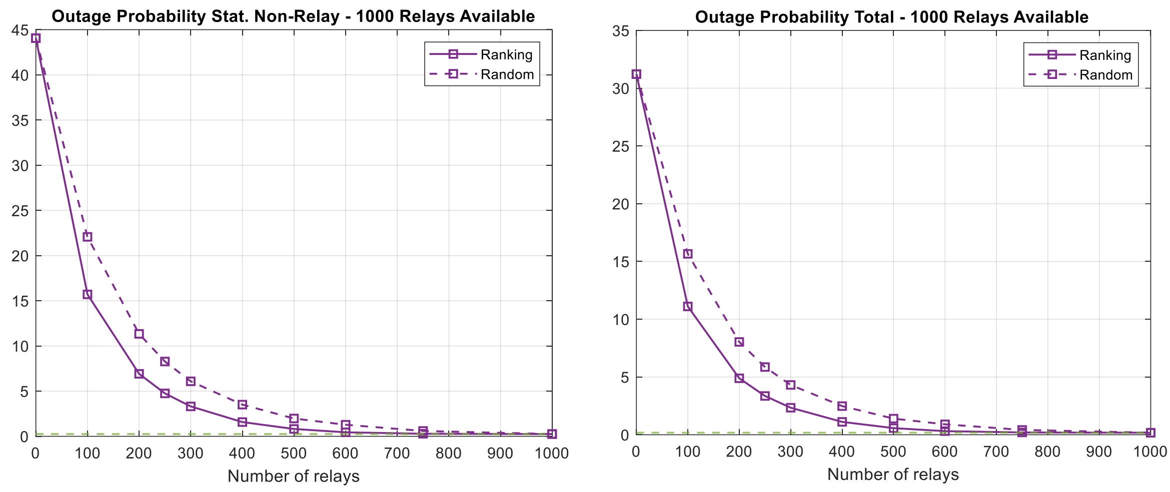
This increase on the introduced improvement is logical, given that there are more users in indoor locations, where the conditions offered by the BSs are worse, so the relays are more useful in this situation.

The total outage probability, on the other hand, follows the same tendency as in timeframe 1. However, the values are remarkably higher than before, given that timeframe 2 considers a bigger number of indoor users. In this case, we can see that the total outage probability is reduced by a 64% when comparing the case with 100 active relays and the case with no relays in all three cases.



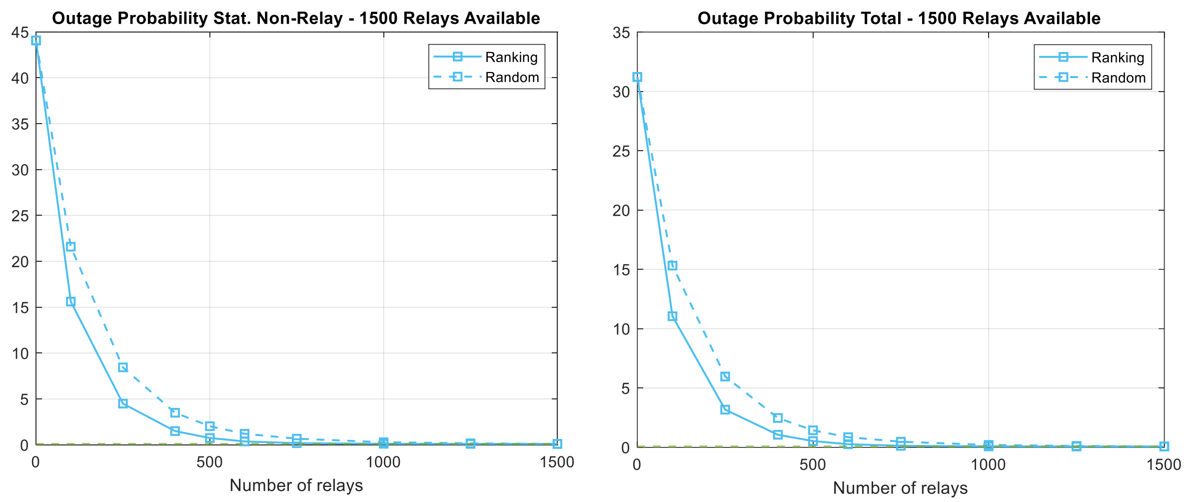
a) b)

Figure 6.8: Outage probability values of indoor stationary non-relays (a) and total (b) with 500 available relays in timeframe 2



a) b)

Figure 6.9: Outage probability values of indoor stationary non-relays (a) and total (b) with 1000 available relays in timeframe 2



a) b)

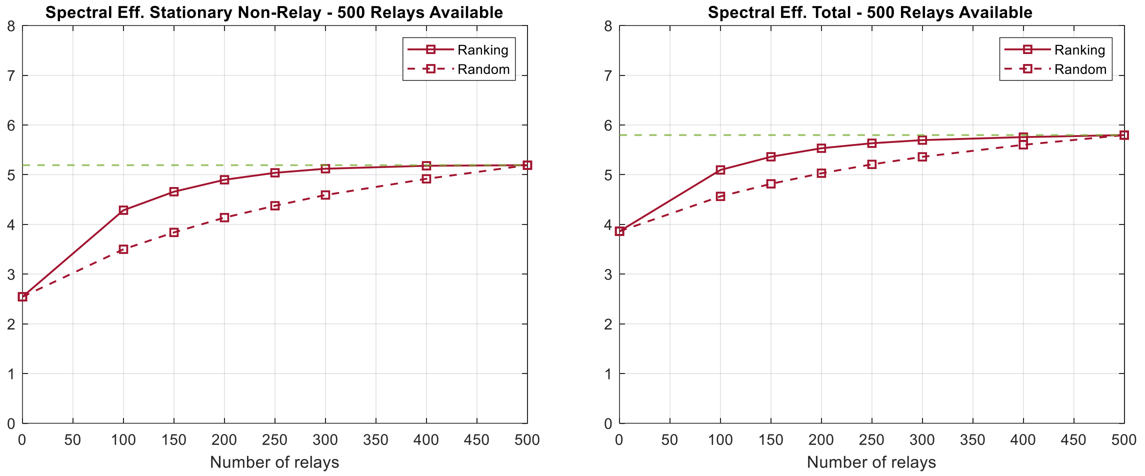
Figure 6.10: Outage probability values of indoor stationary non-relays (a) and total (b) with 1500 available relays in timeframe 2

Figures 6.11, 6.12 and 6.13 show the comparison of the spectral efficiencies of indoor stationary UEs and the total average spectral efficiencies obtained by activating the top relays of the ranking (continuous lines) or activating the relays randomly (dotted lines), for the cases of 500, 1000 and 1500 relays available.

This time, the improvement introduced by the selection of the relays according to the ranking is a little higher than in timeframe 1. For example, when activating 100 relays, the obtained total spectral efficiency grows by 11.6% with 500 relays available and by 14.3% with 1000 and 1500 relays available when comparing the random selection and the ranking based one.

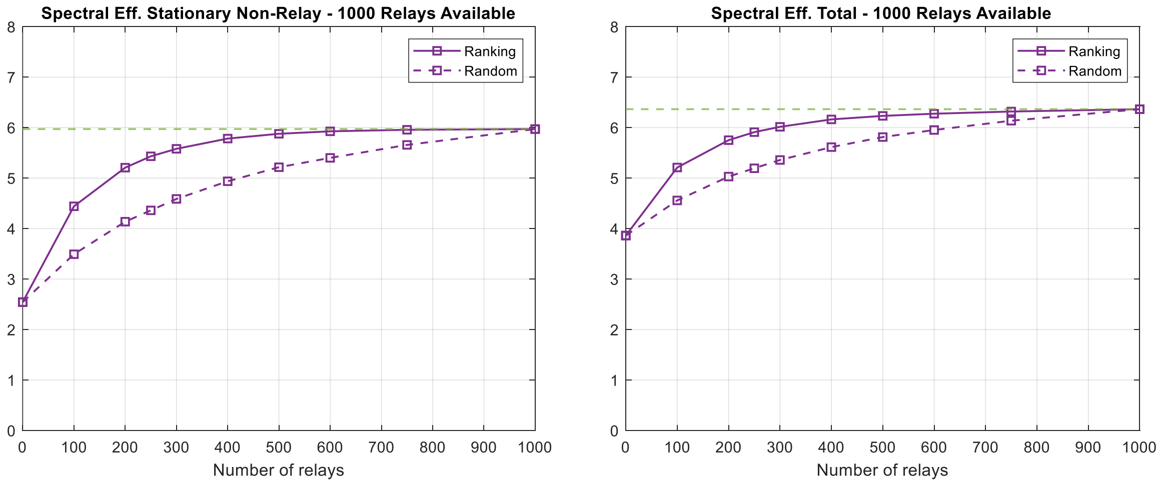
The spectral efficiency of the indoor stationary users is remarkably improved, growing by 22% with 100 active relays and 500 relays available, and by 27% with 1000 and 1500 relays available.

Besides, the activation of 100 relays according to the ranking introduces an increase of 68.5% in the spectral efficiency of indoor stationary UEs, as opposed to when there are no active relays, in the case with 500 relays available. With 1000 and 1500 available relays, on the other hand, this increase goes up to 75%. With the random relay activation, however, the spectral efficiency only increases by 37%.



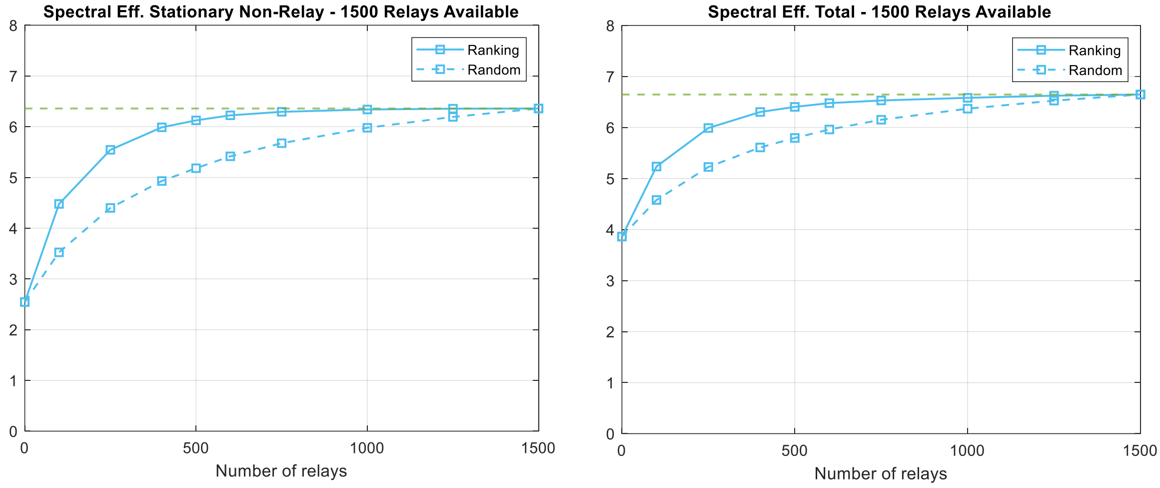
a) b)

Figure 6.11: Spectral efficiency values of indoor stationary non-relays (a) and total (b) with 500 available relays in timeframe 2



a) b)

Figure 6.12: Spectral efficiency values of indoor stationary non-relays (a) and total (b) with 1000 available relays in timeframe 2



a) b)

Figure 6.13: Spectral efficiency values of indoor stationary non-relays (a) and total (b) with 1500 available relays in timeframe 2

7. Budget

In order to compute the budget needed for the project, given that no prototype has been developed, we only need to consider the cost of the used digital tools and the dedicated work hours.

Regarding the cost of the work hours, we will consider the salary of a junior engineer as 15 €/hour and 900 worked hours (equivalent to 30 ECTS credits):

$$15\ €/h\ * 900h\ = 13500€$$

Regarding the used software, we need to take into account the cost of the licences needed:

- Matlab student licence: 35€
- Microsoft Office 365: 7€/month for 9 months → 63€

Therefore, the total cost of the project is shown in the following table:

Total Digital Tools	98€
Total Salary	13500€
Total	13598€

Table 7.1: Total project budget

8. Conclusions and future development

This project had the aim of studying and analysing the deployment of a network using UEs as relaying devices in order to achieve an augmented RAN that would be able to offer a better performance to the users, including higher capacity and lower outage probability, all encompassed in a vision of a Beyond 5G scenario.

In order to do so, a simulator tool developed in matlab by the Mobile Communications Research Group from UPC has been used, to which some enhancements have been added so that we could achieve the wanted results. This simulator recreates an urban scenario with different types of users (pedestrians, vehicles and stationary users) moving around it, which get connected and disconnected to the network, recreating various traffic distribution situations.

By means of this tool, a wide range of simulations have been performed under different configuration parameters, allowing the analysis of the impact that these parameters have on the network performance. The obtained results have been evaluated and quantified in terms of the spectral efficiency and the outage probability observed by the network users.

From these studies we may see that the usage of the stationary UEs as relays can improve the network performance by increasing the spectral efficiency of stationary UEs by up to a 287% in the case where the BSs transmit at 15 dBm and using 80% of the stationary UEs as relay nodes; while the outage probability of indoor users is reduced, achieving decreases of up to 98.75% when comparing the case with no relays and the case with 80% involvement factor.

Next, the relay nodes have been characterised according to different criteria so that we may evaluate their effect on the network. Three different criteria were analysed: number of UEs served by the relay, introduced spectral efficiency improvement and number of UEs served by the relay that were in outage with their serving BS. After monitoring these criteria, the values and the positions of the relays of the three categories have been analysed, so that we could determine the characteristics of the relays that are most helpful to the network.

This characterisation process allowed creating a ranking of the relays according to their usefulness. This concept of relay ranking was then further developed to formulate a relay selection strategy and its possible practical implementation based on a network digital twin, considering the simulator as a network digital twin which allows offline characterisation of the ranking of the candidate relays. This study was performed for two different timeframes involving two different spatial traffic distributions, one corresponding to a morning timeframe and the second one corresponding to an evening timeframe.

The results obtained with this approach were then also evaluated by means of spectral efficiency and outage probability of the UEs.

This relay selection strategy has proven to introduce improvements of up to 31% with 100 active relays in terms of outage probability of indoor stationary users as opposed to a random relay activation approach. Besides, the spectral efficiency of the indoor stationary UEs has been shown to increase by up to 27% in this same case.

In addition, the activation of the top 100 relays of the ranking has proven to introduce an increase of up to a 75% in terms of spectral efficiency and an improvement of up to a 66% in outage probability, as opposed to when there are no relays active in the network.

As main conclusions inferred from this research work, we should note the following:

- The usage of User Equipments as relaying nodes can bring great performance improvements to wireless networks, and these introduced improvements are more significant when the initial network configuration conditions are less favourable, such as in the cases when the scenario has less BSs or when the transmission power of the BSs is lower.
- The proposed approach brings the most notable improvement to the users which are located in indoor areas, where the propagation conditions are worse and the signal transmitted by the BSs is weaker.
- The performed studies have shown that developing an adequate strategy for the relay activation can lead to a more efficient usage of the resources, achieving better results with the same amount of active relays.

Regarding the work that may be developed in the future, there are several areas that yet could be studied and developed.

On the one hand, regarding the simulator tool itself, it has been mentioned that it does not consider any interference. A possible development would be to upgrade the tool so that it would take the interference into account when computing the SNR, considering both interference between base stations and between relays.

Besides, considering the users' mobility, a different handover criterion could be designed and added to the system, since now the UE connects to the BS or relay that offers the best SNR, as explained in section 3.1.4.

Regarding the overall system, on the other hand, considering the architecture described by the O-RAN Alliance, the deployment of AI/ML techniques on the RAN should also be studied, which could allow an autonomous and efficient strategy for the relay activation phase.

Finally, the AI/ML techniques could also be developed at the UE side, given their powerful processing capabilities; which could also be helpful for developing policies for an efficient usage of the existing resources.

Bibliography

[1] Polese, M., Bonati, L., D'Oro, S., Basagni, S., & Melodia, T. (2022). Understanding O-RAN: Architecture, Interfaces, Algorithms, Security, and Research Challenges. [online] Retrieved May 2022, from https://arxiv.org/pdf/2202.01032.pdf

[2] Ericsson (2021) An intelligent platform: The use of O-RAN's SMO as the enabler for openness and innovation in the RAN domain [Whitepaper].

[3] O-Ran Alliance (2018) O-RAN: Towards an Open and Smart RAN [Whitepaper].

[4] Business Wire. (2021). Businesswire. Retrieved May 2022, from https://www.businesswire.com/news/home/20210111005829/en/The-%E2%80%9CCherry%E2%80%9D-Release-of-O-RAN-Open-Software-Moves-the-O-RAN-Ecosystem-Closer-to-Deployment-in-Mobile-Networks-Around-the-Globe

[5] Dahlman, E., Parkvall, S., Skold, J., & Sköld, J. (2013). 4G - LTE/LTE-Advanced for Mobile Broadband. Amsterdam University Press.

[6] LTE Relay: 4G LTE Advanced Relaying » Electronics Notes. (n.d.). Electronics Notes. Retrieved May 2022, from https://www.electronics-notes.com/articles/connectivity/4g-lte-long-term-evolution/lte-relaying.php

[7] Hoymann, C., Chen, W., Montojo, J., Golitschek, A., Koutsimanis, C., & Shen, X. (2012). Relaying operation in 3GPP LTE: challenges and solutions. IEEE Communications Magazine, 50(2), 156–162. https://doi.org/10.1109/mcom.2012.6146495

[8] Madapatha, C., Makki, B., Fang, C., Teyeb, O., Dahlman, E., Alouini, M. S., & Svensson, T. (2020). On Integrated Access and Backhaul Networks: Current Status and Potentials. IEEE Open Journal of the Communications Society, 1, 1374–1389. https://doi.org/10.1109/ojcoms.2020.3022529

[9] Polese, M., Giordani, M., Zugno, T., Roy, A., Goyal, S., Castor, D., & Zorzi, M. (2020). Integrated Access and Backhaul in 5G mmWave Networks: Potential and Challenges. IEEE Communications Magazine, 58(3), 62–68. https://doi.org/10.1109/mcom.001.1900346

[10] Flamini, R., de Donno, D., Gambini, J., Giuppi, F., Mazzucco, C., Milani, A., & Resteghini, L. (2022). Towards a Heterogeneous Smart Electromagnetic Environment for Millimeter-Wave Communications: An Industrial Viewpoint. IEEE Transactions on Antennas and Propagation, 1. https://doi.org/10.1109/tap.2022.3151978

[11] J. Perez-Romero, O. Sallent " Leveraging User Equipment for Radio Access Network Augmentation". In IEEE Conference on Standards for Communications and Networking (CSCN) Barcelona, Spain pp. 115-119. doi: 978-1-6654-2349-6/21/$31.00

[12] Asadi, A., Wang, Q., & Mancuso, V. (2014). A Survey on Device-to-Device Communication in Cellular Networks. IEEE Communications Surveys & Tutorials, 16(4), 1801–1819. https://doi.org/10.1109/comst.2014.2319555

[13] Tehrani, M. N., Uysal, M., & Yanikomeroglu, H. (2014). Device-to-device communication in 5G cellular networks: challenges, solutions, and future directions. IEEE Communications Magazine, 52(5), 86–92. https://doi.org/10.1109/mcom.2014.6815897

[14] Schlienz, A. Roessler, "Device to Device communication in LTE", Rohde & Schwarz [Whitepaper].

[15] Difference between Inband D2D vs Outband D2D communication. (n.d.). RF Wireless World. Retrieved May 2022, from https://www.rfwireless-world.com/Terminology/InBand-D2D-communication-vs-Outband-D2D-communication.html

[16] 3GPP TR 38.901 16.1.0 "Study on channel model for frequencies from 0.5 to 100 GHz (Release 16)", December, 2019.

[17] Siemens AG, "TDD UE-UE Interference Simulations", R4-030189,TSG-RAN WG4 meeting #26, Madrid, February, 2003.

[18] Jacobson, K. R., & Krzymień, W. A. (2011). Multihop relaying and multiple antenna techniques: performance trade-offs in cellular systems. *EURASIP Journal on Wireless Communications and Networking*, *2011*(1). https://doi.org/10.1186/1687-1499-2011-65

[19] BenMimoune, A., Khasawneh, F. A., Rong, B., & Kadoch, M. (2017). Dynamic joint resource allocation and relay selection for 5G multi-hop relay systems. *Telecommunication Systems*, *66*(2), 283–294. https://doi.org/10.1007/s11235-017-0286-3