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MASTER

Cellular relaying for industry 4.0

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Cellular relaying for industry 4.0

Master Thesis

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Abstract

In recent years technology has developed at a phenomenal rate and Internet of Things (IoT) has played a vital role in this development. The recent development of 5G has opened new doors for cellular-based IoT systems and in particular critical-IoT applications. Critical-IoT applications have stringent Ultra-Reliable Low-Latency Communication (URLLC) requirements. One of the critical-IoT applications is 'Factory of Future' (FoF). In FoF, synchronization of various IoT devices is essential and this synchronization demands Ultra-Reliable communication with low latency. One of the methods to achieve this high transmission reliability requirement is to use User Equipment (UE) relaying, where the UE can switch its path of transmission if the connection is poor or broken. In this paper, we investigate the necessary design choices to implement a relaying network and also analyze the implementation of cellular-based relaying network in the factories. Further in this paper, we demonstrate the suitability of various relay selection algorithms to develop a relaying network for factories of future. Finally, we discuss the parameters to consider the development of relaying networks.

Acknowledgement

This master's project report marks the culmination of my studies at the Technical University of Eindhoven for obtaining a Master of Science (MSc) degree in Embedded Systems (Networking). The graduation project experience for me was a bit different than expected due to the strange corona times. Nevertheless working on this project helped get a deeper understanding of cellular communications and wireless sensor networks. This project brought me out of comfort zone to explore the domain of cellular-based internet of things applications. The successful completion of this project would not have been possible without constant support and guidance from several people. First of all, I would like to thank the TNO network department for providing me with an opportunity to work on this project with their research expertise. TNO ensured that I was provided with all the necessary resources to conduct my research with great quality. Especially, I would like to thank all the colleagues in the network department who shared their knowledge which helped me understand the field of cellular communication. Further, I would also like to thank my colleagues who helped me develop my critical thinking and analytical skills.

I would like to thank Sjors Braam, my daily supervisor, for devoting his time to check on my progress and helping me to find the fix for the various challenges that I faced during the development of this project and its simulation environment. His coding experience and field expertise helped me lay the path for this project and implement a few modules for the simulated environment. I would also like to express my sincere gratitude to Sonia Heemstra, my supervisor at TU eindhoven, for her advises in shaping my research goals and critical feedback that help me obtain the mature results for this project. Although the feedbacks were quite challenging and it helped me improve the quality of this project. I would also like to thank the members of the jury, Alexios Balatsoukas Stimming and Georgios Exarchakos for agreeing to be a part of my thesis committee. I would also like to thank them for their feedback through the projects, which helped me shape the project. I would like to use this opportunity to thank Yohan Toh, Yonatan Woldeleul, Remco Litjens, Haibin Zhang, Kallol Das, Ljupco Jorguseski, Ashish Panda, João Morais and Dick van Smirren for their support and feedbacks that help me build the knowledge of telecommunications for this project.

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Aadesh Shah

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Chapter 1

Introduction

This report represents the result of Graduation Project which has been undertaken at **The Netherlands Organization for Applied Scientific Research (TNO)**, between 14th October 2019 and 14th July 2020, as a part of my Master's curriculum at Technical University of Eindhoven. This section of the report gives an overview of the problem, introduces the company and describes the scope of this document.

1.1 Scope of the problem

IoT is a revolutionary technology where several smart devices or sensor nodes are connected to perform a designated task. For IoT devices, the use of superior communication technology plays a vital role to meet the critical requirements of availability, reliability and latency. In recent years, the demand for Critical-IoT applications like Vehicle-to-Vehicle communication, Factories of the Future (FoF) and e-Health services has increased dramatically. One of the basic requirements of these applications is seamless connectivity with Ultra-Reliable Low-Latency Communication (URLLC)[16]. These requirements have opened the doors to develop new and better communication technologies like 5G.
Previous cellular communication technologies like 3G and 4G have focused on voice and data communication, while 5G improves and extends this focus for diverse IoT applications. 5G aims to achieve higher reliability with low latency which solves most of the issues for Critical-IoT applications. But there are some issues such as broken links, weak signals or coverage loss which affect the transmission reliability of the system. In some cases, there can be an obstruction that can be by passed by relaying via another User Equipment (UE) or other devices. But relaying has its drawbacks too. The goal of this graduation project is to investigate and design relaying solutions to overcome the issue of transmission reliability for Critical-IoT applications like factories of the future.

1.2 About the company

The Netherlands Organization for Applied Scientific Research (TNO) is an independent research organization. TNO's mission is to connect people and knowledge to create innovations that boost the sustainable competitive strength of companies and the well-being of society. TNO cooperates with partners and focuses on nine social domains. TNO was founded in 1932 under the Dutch law. As an organization governed by the public law, TNO has an independent position and based on these conditions TNO provides solutions to the major challenges our societies face.

1.3 Overview of the report

This document is structured as follows. Chapter 2 talks about the related work and the contributions of this project. Chapter 3 explores the factories of the future, its requirements, layout and its challenges. Further, in Chapter 4, we discuss the approach of the stated problem where we explore the concepts of relaying and cellular-based relaying. Additionally, in this chapter, we make the necessary design choices for relaying networks. In chapter 5, explores the simulation setup and the implementation of simulated relay network. Chapter 6 evaluates the implementation of simulated relaying network and explains the results of different simulation campaigns. Finally, the last chapter concludes the findings of this graduation project and provides an insight into how the relaying network can be improved further to implement them in the factories of the future.

Chapter 2

Literature Review

There has been constant research going on to determine the potential of relaying for URLLC applications like factory automation, where people have focused on different aspects of relaying networks. For instance, Pan et al. [33] demonstrated the use of an unmanned aerial vehicle as a relay node to bypass a wall and meet the stringent URLLC requirements. The authors developed an algorithm which optimizes the resource allocation and location of a relay node to achieve the desired results. Their study discusses the effects of searching a relay node based on its height/location. Another interesting research in terms of URLLC communication for factories is discussed in [10], where the authors proposed a mobile ad-hoc network, based on the swarms created by the dragonflies. Bhardwaj et al. propose a mathematical model where various formations of dragonflies swarms are replicated to develop an ad-hoc network which can achieve high reliability with low latency. The mathematical results show performance improvements where the topology of the network changes according to the network demand, but the actual implementation of the network with cellular D2D still needs to be researched. Furthermore, [31] discussed application-specific relay selection and they classify relays according to the scenarios like critical delay, high mobility and green communication. Nomikos et al. formulated three relay selection policies by considering the requirements of each scenario. Further, the authors numerically evaluate average throughput, delay and power for each relay selection policies with their corresponding scenarios. The paper provides insights about the metric for relay selection and what the necessary goals are according to the scenarios. However, the authors do not explore how relay selection can be implemented with actual standards of cellular communication and how other parameters of relaying can impact the network.

In the LTE standard, there is a defined protocol which can help determine the signal strength of relay UEs in proximity and this value of signal strength can be used to select a relay node [4]. Use of signal strength as a metric for node selection is proven to be beneficial for various wireless routing protocols. Park et al. [34] compared the implementation of traditional ad hoc on-demand distance vector protocol (AODV) with a signal strength based AODV protocol. Here, the results show that signal strength based AODV protocol performs significantly well in terms of packet reception rate and average end to end latency with a 45 per cent less routing overhead. Similar results can be observed in [13], where the proposed signal strength based AODV has a 4 per cent higher packet reception rate and 7 per cent lower latency compared to traditional AODV. The results of these papers clearly show the benefits of using signal strength as a selection metric for relaying. However, relay selection according to the signal strength in cellular-based D2D communication is yet to be implemented and therefore there has been extensive research in that direction. Relay selection can be either centralized or distributed. Huang et al. [21] discussed centralized relay selection protocol where the base station governs the selection procedure. The results of [21] show an improvement of service time compared to other algorithms but the added delay due to additional signalling and delays are not considered, with their focus being on connection time of UEs. On the other hand, Ohtsuji et al. [32] described a distributed relay selection algorithm

where the link between remote UE and relay UE and even the relay UE uplink link quality is considered for selection. Although their results show substantial improvements where 99 per cent of out-of-coverage users meet the throughput requirement, the methodology to share the relay UE link quality with remote UE is not discussed.
In general, to the best of my knowledge, the algorithms mentioned above do not explore the system-level implementation for ProSe protocol which enables the functionality of UE-to-Network Relay for cellular networks.

In [18], Gamboa et al. provide a system-level evaluation of UE-to-Network Relay. The authors explore the usability of relaying link called sidelink in addition to the existing uplink and downlink in cellular communication. The results explain the design and implementation of sidelinks in LTE. The evaluation shows the impact of ProSe features like sidelink period, increase in sidelink traffic and the sidelink timers. The implementation in [18] is generic and does not focus on a particular domain such as factory automation or URLLC applications. Whereas, Munz et al. [30] provide an empirical study on using ProSe based D2D relaying in 5G for factory automation. The results of this study are mostly based on centralised relay selection and resource allocation. Here the authors talked about the impact of re-transmission, relaying and frequency diversity on packet error rate. The paper clearly shows the decrease in packet error rate in a factory environment due to relaying. Additionally, the authors even discuss the impacts and benefits of selecting a relay according to signal strength. However, Munz et al. did not discuss the impact of latency due to relaying in details and effects of an actual factory network with multiple nodes.

In this project, we focus on the investigating system-level implementation of UE-to-network relaying for factories with an emphasis on exploring the added latency due to relaying. Additionally, we propose a hybrid relay selection algorithm where the nodes can determine their signal strength from information sent by the base station and resources are selected by the nodes themselves. In the further sections, we discuss the requirements for factory automation, network layout, the impact of relaying, design choices for the proposed relaying network and potential relay selection algorithms.

Chapter 3

Background

3.1 Domain description and basic requirements

IoT applications will improve the quality of human lives in every possible way. One of the domains that plays an essential role in our lives are factories. Factories involve manufacturing, logistics, supply chain management and other processes. Combining these processes with IoT would not only increase the efficiency but also reduce the stakes of human lives for critical jobs. Factory automation with IoT is popularly known as 'Factory of Future' (FoF) or industry 4.0. The FoF applications require high reliability, high availability and low latency for communication.

Typically, the reliability and availability of wired communication are promising but for an industrial setup, as envisioned for FoF where there will be hundreds of Automated Guided Vehicles (AGVs) or mobile drones and other robots, wired communication would seem impractical and not scalable. Wireless communication would be the only solution to control and synchronize these mobile devices. Akpakwu et al. [8] stated that for industrial applications, the network must have maximum reliability with a latency between 10 and 500 milliseconds (ms). Some of these applications need a network which provides reliability of 99.999% within the end-to-end latency constraint of 10 ms [6]. Some critical applications even demand a network which has lower latency constraints like 5 ms for the reliability requirement of 99.999%.

3.1.1 Wireless technology requirement

IoT applications generally have requirements such as low power consumption, network scalability (increase the size of the network), long battery life and long-range. Short-range communication technologies like Zigbee, Bluetooth, Wi-Fi are not designed for long-range communication, hence they are not easy to configure for long-range transmissions. For long-range communications, the commonly used technologies are Sigfox, Long Range (LoRa) and cellular communication. Depending on the application, FoF may require support for Quality of Service (QoS), low power consumption and long-range communication.

Short-range radio communications have problems with extended coverage wherein Sigfox and LoRa cannot provide high reliability and low latency. The latter is due to the unlicensed spectrum band usage and asynchronous communication protocols which result in very high communication interference [27]. Extensive research has been conducted to develop critical-IoT applications using 5G or Wi-Fi. For instance, Vehicle to everything (V2X) communication has an ongoing conflict on the choice of radio access technology. While some organizations support Wi-Fi-based Dedicated Short Radio Communication (DSRC), others support 5G [14, 9, 25, 7, 3, 39]. Unlike V2X, other applications like smart ports [12, 11, 15, 22, 36, 29], warehouses [19, 24] and factory floors [17, 38] have undertaken intense research to provide test results for developing systems using 5G. In factories, most of the networks are based on wired communications such as PROFIBUS, HART, and CAN [37]. Additionally, there has been significant development to use wireless networks in factories. Most of the wireless protocols are based on the IEEE 802.11 protocol stack. The issue with the IEEE-based protocol stack is the usage of the unlicensed band, hence suffering from interference from all the device or networks using the same spectrum [20]. This limits the IEEE-based protocols to meet the stringent reliability and latency requirements of the factories of the future whereas cellular based networks would have a better performance.

3.2 Layout of factories

The layout for factories of the future is based on the project for one of the TNO's clients. The parameters of the factory are summarized in the table 3.1.

Factory dimensions:	50m x 50m x 6m
Number of base stations:	1
Number of UEs:	$\leq$ 100
UE distribution:	Uniform
UE speed:	$\leq$ 10 km/hr

Table 3.1: Parameters of the factory

In figure 3.1 the proposed representation of the factory according to the specifications can be seen. The proposed factory model consists of 20 assembly lines, 80 robotics arms (4 for each assembly line) and 20 AGVs. The goal of the AGVs is to pick up the raw materials from the inventory and deliver them to the assembly line. For the scope of this project, we would use this layout of the factory to investigate the suitability of relaying network for the factories of the future.

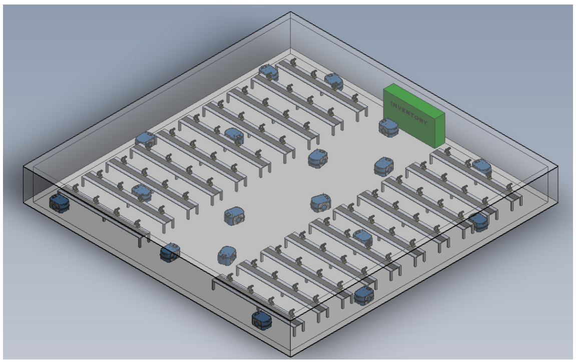


Figure 3.1: Layout of the factory

3.3 Challenges of FoF

Factories of the future are expected to have multiple devices communicating with each other within a small area. This increase in devices can result in network congestion. Additionally, due to the presence of heavy machines and reflective metallic surfaces communication is difficult.

5G promises better connectivity and data rates for critical-IoT applications, but these applications can face connectivity issues due to interference or broken links in factories. Due to these issues, it will be difficult for the UE to communicate to its destination while achieving the desired reliability and latency constraint. Interference or blocking can be caused in a harbour due to a ship or in a factory due to a machine. This problem can be solved by various methods like relaying and beamforming. However, with beamforming, finding an alternative angle around an interference like a heavy machine can be challenging as beamforming works well in line of sight. Whereas with relaying a node can communicate with a nearby node to create an alternative path to deliver data to its destination, but this can increase the latency of the network. Hence relaying can be used where beamforming is hard to implement. For our application, relaying would be a promising solution as it is easy to implement, cost-effective and adaptive. 5G enables the device to device communication where one UE can communicate with another UE without any direct communication link with the network. Using 5G based UE-to-network relaying would help to enhance the reliability of FoF applications but might increase the latency of the network.

To investigate the effects of relaying in a factory, in the next chapter we take a closer look at the problem and decide on necessary design parameters which would be helpful to implement relaying network in the factories. Further in the chapter, we would discuss the implementation of relaying network in a simulated environment where the chosen design parameters can be evaluated.

Chapter 4

Approach

4.1 Problem analysis

In the factory environment, the use of wireless communication can be challenging at times. Reliable communication is not always possible due to hostile radio environments, i.e. reflective metallic facilities, shadowing by large equipment, interference from machines and so on. These conditions could lead to coverage loss, blocking or interference of radio signal at certain locations. The coverage loss and blocking of signals due to interference make line-of-sight communication between source and destination difficult in FoF scenario, where achieving URLLC is the highest priority.

To meet the constraint of URLLC and solve the issue of blocking and coverage loss, the source UE can use relaying, where it can switch between transmission paths and communicate to the nearby node using multiple radio access technologies (RAT) or frequencies to increase the transmission reliability. Relaying tries to solve issues faced by IoT devices, where the UE can communicate with its destination through its neighbour(s) to overcome high interference and low coverage. With relaying, IoT network technologies can promise higher availability and reliability, while fulfilling latency requirement would be a critical task. It is important to achieve higher reliability while considering latency, as each hop adds latency and the network should also ensure the signal quality of each hop is good. Hence to increase the transmission reliability of the system by relaying, choice of communication technology which provides reliable and low latency communication would be the key.

4.2 Relaying

In communication, relaying is a technique where the signals or information is received from a location and forwarded to another location[1]. Relaying has been often proposed in wireless communication, where the source and the destination communicate with each other using static or dynamic nodes. Relaying plays an essential part in improving the transmission reliability of the system. A well-known example of relaying are mobile hotspots, where one device provides its cellular data to other devices which do not have access to cellular data.

The basic concept of relaying for cellular communication is illustrated in Figure 4.1. If the default communication link of a UE (e.g. a LTE link) is unavailable due to blockage or interference, the UE will use the nearby UE(s) as a relay node(s) to reach the destination node. Although in the figure a basic single-hop relaying is shown, it is possible to extend the concept of relaying for systems which can be used for data duplication, a multi-hop system or even a multi-link system if necessary. The network design for the UE-to-network relaying in factories can be seen later in this chapter.

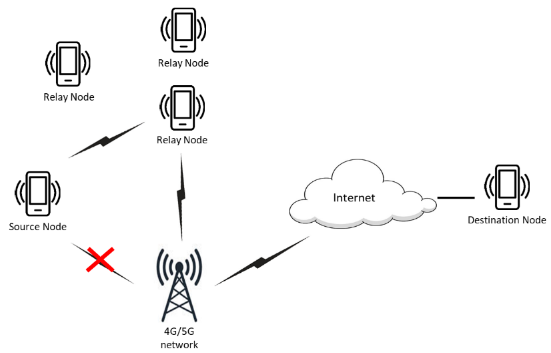


Figure 4.1: Relaying concept for mobile devices

4.2.1 Relaying challenges

Relaying has many advantages like being low-cost, can provide extended coverage or no need for extra infrastructure. However, several challenges need to be addressed to provide a robust solution for the stated problem. Some of the issues are stated below:

1. When to do relaying: On what parameters the source node decides to relay via nearby nodes.
2. Which technology to use: In several ways relaying can be performed. Should the technology for relaying and point to point connection be different?
3. Routing: How to do routing, proactive or reactive?
4. Latency constraints: Relaying generally adds delay due to the hops. Hence improving reliability with latency constraints can be challenging.

4.3 Design choices

Looking at the relaying challenges and the factory layout mentioned in 3 we proceed further to develop the relaying network which can achieve higher reliability. For the development of an efficient relaying network, several design parameters are considered. These design parameters and their choices are discussed further in this section.

4.3.1 Selection of relay nodes

In the proposed factory model, we have 20 AGVs which are mobile nodes. Similarly, we consider the robotic arms to be static nodes. For our design, all the static nodes can act as a relay node as they are available everywhere in a factory. Even in other scenarios like harbours or warehouses nodes like gantry cranes or shelves are static and can be used as relay nodes. Choosing all the static nodes as relay nodes can improve the availability of relay nodes and at the same time no additional infrastructure is required for relaying services. However, it is important that the relay node considers it's signal strength with the base station before providing relay services because a relay node with bad signal strength might lose a packet or need another hop which can affect the reliability of the network. The implementation of nodes providing relaying services is discussed later in this chapter.

4.3.2 Selection of technology

Here we would discuss the technology that can be used for relaying. As per the discussion from 3 we have learnt we need wireless technology for FoF. From all the wireless technologies the two most suitable technologies are cellular communication and Wi-Fi. Cellular based technologies enable relaying by using the device to device (D2D) communication which is proposed by the third-generation partnership project (3GPP) in release 12. It would be useful to develop a network which is uniform and completely based on cellular communications as using two different technologies would require infrastructure for both the technologies. Additionally, there have been analytical studies that have shown that cellular-based D2D can provide lower delays and more energy savings compared to other short-range communication technologies such as Wi-Fi [28]. Hence, for the proposed factory model, cellular-based D2D would be one of the optimal choices as it would provide uniformity to the network.

4.3.3 Location of base station

It is important to decide on the location of the base station as it should be positioned such that all UEs are in-coverage. The best location to provide coverage to most of the UEs would be on the ceiling at the centre of the factory.
In addition, with the advancement of cellular networks, it is possible to create a private cellular network which can be used for the proposed factory model. A private network has several benefits, which are as follows:

1. Dedicated resources
2. Reduced interference from third parties.
3. Increased security

Hence the location of the base station on the ceiling at the centre and a private network would ensure good coverage for all the UEs unless there is some interference or blocking due to a piece of machinery and other devices in the factories.

4.3.4 Metric for relay selection

In this section, we would decide on the metric that can be used for selection of relay nodes.
In cellular communication, the strength of the signal is dependent on many factors like noise, interference, distance to name a few and these factors have an impact on transmission and reception power of the UE. One of the key measurement metric for signal quality in cellular communication is the Reference Signal Received Power (RSRP). RSRP is the average power of the Resource Elements (RE) that carry cell-specific Reference Signals (RS) over the entire bandwidth. In table 4.1, one can see the signal quality for the corresponding RSRP values.

Signal Quality	RSRP (dbm)
Excellent	> -84
Good	-85 to -102
Fair	-103 to -111
Poor	<-111

Table 4.1: Signal quality as per RSRP values

For relaying, the remote node should select a relay node which has a good connection with the base station, good connection with itself and the relay node should be nearby. Hence a metric for relay selection should consider the RSRP for the relay node and base station links, the RSRP for the remote node and relay node link and the positions of all the nodes. Further in this section, we look at how the choices for the design parameters we made can be implemented with cellular technologies.

4.4 Device to device communication in LTE

In the previous sections, we have decided on the candidates for relay nodes, choice of technology, the location of devices with the type of the network and the metric for relay selection. Where the choice of the metric was to use RSRP of remote node and position of the remote node and probable relay node to choose the best node for relaying. In this section, we discuss the possibility of using the metric for relay selection with cellular networks with its design and implementation. Further in this section we also make design choices that will focus on cellular-based UE-to-network relay networks.

4.4.1 Proximity services

Proximity Services (ProSe) were first introduced in 3GPP release 12 of LTE standard enables device to device communication for nearby devices in a cellular networks. The investigation of ProSe based UE-to-network relaying in this project is based on 3GPP release 13. ProSe support three scenarios which are mentioned in the figure 4.2.

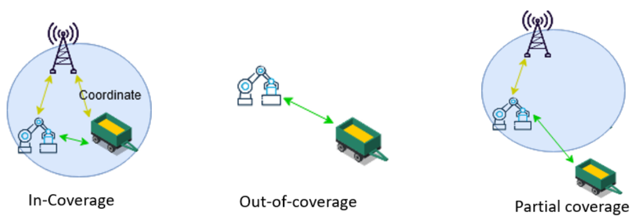


Figure 4.2: Scenarios supported by ProSe

In the figure, one can see three scenarios namely in-coverage, out-of-coverage and partial coverage. For the in-coverage and partial coverage, only the relay node or both relay node and the remote node are in the coverage area of the base station (as denoted by the blue area), this means the base station can control or assign the resources for the D2D communication. Whereas for the out-of-coverage scenario the communications resources are allotted as per the preconfigured information. According to our proposed factory model, where we consider all the static nodes are relay nodes such that a relay node would always be in-coverage of the base station. Therefore for our network, out-of-coverage scenario would not be applicable.

As ProSe opens doors for developing efficient cellular networks, several new interfaces are added to the existing cellular network architecture. The modified network architecture can be seen in figure 4.3

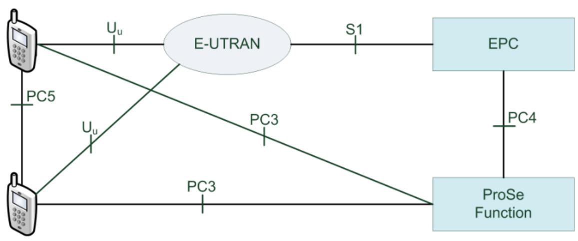


Figure 4.3: Network architecture for ProSe
[23]

From the viewpoint of the UE, the two most important interfaces are PC5 and PC3. The PC5 interface also known as sidelink at the physical layer enables the communication between two UEs.

The PC3 interface is used by the UE to communicate with the ProSe function, which provides information for the network-related actions.

The development of ProSe has enabled UE-to-network relaying functionality for cellular networks which will be our focus for the rest of the section.

4.4.2 UE to network relaying

The figure 4.4 shows the usage of ProSe for relaying. All nodes in the figure support ProSe; there are two types of UE, relay UE and remote UE. The relay node communicate with the base station via conventional UL and DL and uses the sidelink (SL) to communicate with the remote node. However, the remote UE can communicate to the base station directly or via the relay node depending on link quality between the remote UE and base station. If the remote UE has a poor link quality it chooses a relay node and sends the data to the base station via the relay using the SL and the same route can be used for DL communication. There are two methods for resource

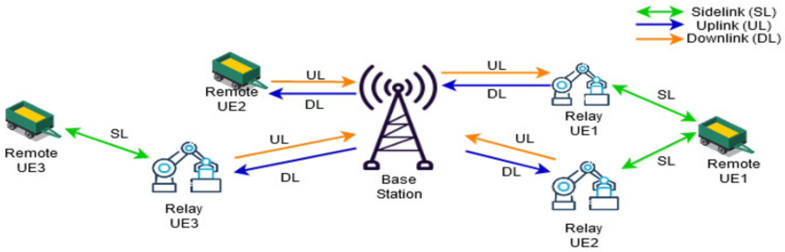


Figure 4.4: UE-to-Network relaying with ProSe

allocation for ProSe based D2D communication which are stated as follows:

1. Base station scheduled (mode 1): Here the base station assigns the resources to the UEs which are seeking resources for the relay services.

2. UE selected (mode 2): In mode 2, the UE selects the resources for relaying from the pool of available resources without any coordination from the base station.

In general, mode 1 type resources allocation is used for in-coverage relaying services whereas mode 2 is used for out-of-coverage resource allocation.

With resource allocation, ProSe also provides two methods for discovering the nearby relay nodes. These methods are mentioned below:

1. Model A: In model A, the node providing relay services periodically broadcast its presence for the remote node.

2. Model B: In model B, the remote node seeking relay services sends the request messages to the nodes providing relaying services.

At this point in the document, we have laid the foundations for relaying and ProSe based D2D communication in cellular networks. Further in this section, we discuss the working of sidelink in cellular networks, design choices for ProSe based UE-to-Network relaying and the possibility of relay selection. Later, in this section, we would also discuss the possible implementations to improve the transmission reliability of the network.

4.4.3 How sidelink works

To set up a successful communication, the remote UE needs to select a relay node, establish a secure connection and setup the IP configuration. After a successful setup, the remote UE can send the data to the relay UE. Figure 4.5 demonstrates six stages that are needed for setting up, communication and maintenance of an end-to-end relaying link. The stages are explained as follows:

Authorization and provision: It is the first stage, where UEs notify to the base station that they support ProSe functionalities [5]. Additionally, through the SidelinkUEinformation message UEs declare their role as a remote node or relay node and request for the radio resources for communication. The core cellular network specifies the resources for ProSe, and broadcast the information using System information blocks 18/19 or sends the message each UE via the Radio Resource Control (RRC) messages [4].

Relay Discovery and selection: Once the network provides the authorization for using ProSe, the remote nodes start to discover the potential relay node using ProSe direct discovery models. The figure shows the usage of model A for discovery, where the relay UE periodically broadcast its eligibility as a relay node. For discovery, the UEs use PC5_Discovery messages for broadcasting and response messages.

In [4], it is defined that minimum signal strength that can be used for the selection procedure. The UEs can detect the signal strength between the relay UE and the remote UE based on the power of the signal which essentially is the RSRP value. The selection procedure of relays is explained further in this section. Based on the selection procedure the remote UE selects the relay UE and sends the selection as a response message for the discovery.

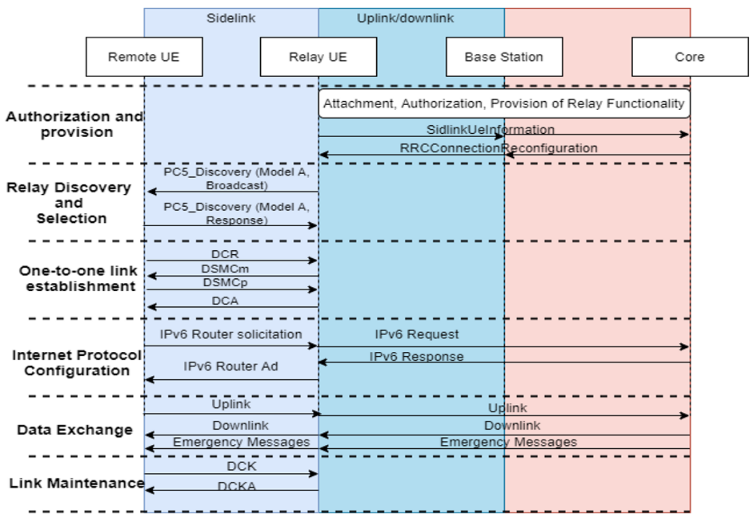


Figure 4.5: UE-to-Network relay protocol signalling for discovery model A

One-to-one link establishment: After discovering and selecting the relay UE, the remote UE sends various signalling messages to establish a one-to-one link with the relay UE. These messages are:

1. Direct communication request (DCR)
2. Direct security mode command (DSMCm)
3. Direct security mode complete (DSMCp)
4. Direct communication Accept (DCA)

Internet protocol configuration: After the successful reception of DCA message, the remote UE starts the IP configuration as per the IEFT standard of sending Router Solicitation messages and responding with Router Advertisement messages. IPv6 is used for the configuration to satisfy the requirements of mission-critical applications [5].

Data exchange: Once the IP configuration is successful the remote UE can now send the data to the base station via the relay node. The diagram shows the message exchange as per the traffic model described in section 5.1.

Link maintenance: Finally, we arrive at the last stage, maintenance this stage is very important as it keeps the established one to one link active. Here the remote UE would send a direct communication keepalive (DCK) message signalling to the attached relay UE, that it might use the link for communication. The relay UE acknowledges the DCK message by sending a direct communication keepalive acknowledge (DCKA) message back to the remote UE, this procedure is periodically repeated to keep the link active.

Sidelink channels

In ProSe there are dedicated resources for discovery, control and data. The Physical Sidelink Discovery Channel (PSDCH) is used to send the discovery messages where the resources are selected from a discovery transmission pool. For the data packet and signalling messages ProSe use Physical Sidelink Shared Channel (PSSCH) where the resource allocation for the messages are indicated by the corresponding Physical Sidelink Control Channel (PSCCH), which repeats periodically in time [2]. This period is known as the SL period.

Sidelink period

As discussed above the sidelink period contains the periodic occurrences of PSCCH and PSSCH channels which are responsible for signalling and sending data in UE-to-Network relay networks. Figure 4.6 shows a timeline describing the sidelink periods. A sidelink period consists of subframes, for example in the figure you can see that one period is consists of 12 subframes. From the 12 subframes, 4 subframes are allotted for PSCCH and the remaining for PSCCH, the length of the channel and the number of resources are configurable. The choice of the length and the resource would be discussed in more detail in 4.4.4.

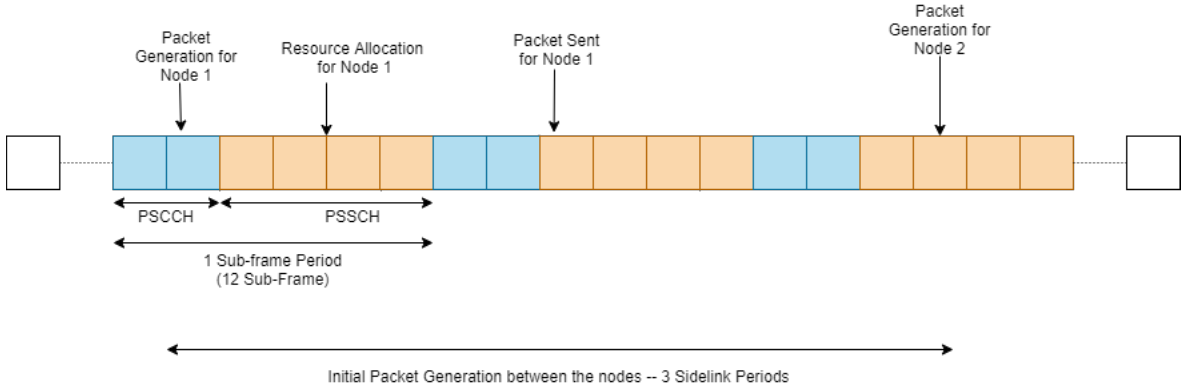


Figure 4.6: Timeline for sidelink periods

In ProSe the data packets are not sent as soon as they are created but rather sent in the next period after the resources are allocated for that packet. The figure shows the packet is created for node 1 in the first period, and the resources are normally assigned 4 ms before the start of next period such that the PSCCH of the next period can signal the corresponding PSSCH about the allotted resources for the data packets. One can also see there is a gap of 3 sidelink periods between the two nodes generating the packets and this gap makes sure there is no collision between the two nodes.

In the sections above we have got a basic understanding of how ProSe work and what are the critical parameters of sidelinks. Further, in the next section, we would discuss about the design parameters and their choices for our proposed relaying network.

4.4.4 Relaying design choices for ProSe

The scope of this project is to define a relaying network which can achieve high reliability even in hostile factory environments. Till this point, we have decided the technology that can be used for relaying, the metric for relay selection, location of the base station and the nodes that can act as relay nodes. Further in this section, we decide the relay specific design parameters concerning ProSe.

Mode selection

As mentioned in the sections above ProSe support two types of modes for resource allocation, mode 1 where the base station assigns the resources to the UEs for relaying whereas in mode 2 the UEs select the resources from a pool of available resources. For the proposed factory model we consider relaying for the situations where links with the base station are weak or broken, hence mode 2 would be a good design choice for the networks as the UEs can choose their resources without the dependency on the base station. Selecting mode 2 for resource allocation also helps to reduce the overhead on the base station, as the node with the weak signal strength would not communicate with the base station, reducing the exchange of signalling messages for assigning resources.

Choosing the discovery model

ProSe supports two discovery models, model A where the Relay UE broadcast its presence periodically and in model B the remote UE would search for relay UE by sending a request. The results in [18] shows that model B takes longer time to discover than model A for the same resource pool configuration. Our goal is to achieve high reliability with stringent latency requirements. Hence model A would be a suitable choice for our network.

Choice of subframe period

Standards for ProSe described in [4] states the configurable period length can be between 40 subframes to 320 subframes. This means the minimum length for a period can be 40, hence a data packet might have to wait for 40 subframes for transmission if the packet is generated at the start of any period. Hence it is important to choose the lowest possible sidelink period, which would reduce the packet wait time and improve overall network performance. To see the behaviour of shorter sidelink periods, we have tried to develop shorter periods in the simulation environments which will be discussed in chapter 5.

4.4.5 How to improve the reliability

The goal of this project is to design a network which can improve the transmission reliability of relaying networks in the factories. In this section, we explore the impact on reliability due to ProSe based relaying for cellular networks and how reliability can be improved using cellular UE-to-network relaying.

Reasons for packet loss using sidelinks

The architecture of cellular networks has been modified to support ProSe, so now in cellular networks, we have an additional link called SL for communication with the existing UL and DL. Hence, before we take a look at improving the reliability of the network, let us see how packets can be lost using sidelinks. The reasons for packet loss due to sidelink are mentioned below:

1. Collisions on the Sidelink: All UEs (Remote and relay) contend for the same resource in the pool. Hence there is a possibility of two UEs transmit using the same resource, which increases the probability of collisions on the sidelink.
2. Collisions between SL and Uplink: As UL and SL use the same spectrum for transmission [5] it increases the chances of collisions between the two links unless scheduled properly in the frequency and time domain.
3. Half duplex: Most of the UEs support half-duplex, which means they can only transmit or receive at a time but can not do both together when they use sidelink. Hence, if a UE has to transmit a packet, it can not receive a packet sent to it which leads to packet loss on sidelinks.
4. Priority of uplink over sidelink: The Relay UEs can only transmit in one link each subframe, and UL transmissions have priority over the SL. Which can lead to packet loss for SL.

At this point of the document, we have seen the factors that can have an impact on reliability of a network. In the next section we would look at the possible solutions that could improve the transmission reliability of the network.

Rank based relay selection with multiple links

One of the major issues in factory networks is blocking. One of the reasons for blocking can be heavy machines and they can be static or mobile. In cases when the machine is mobile, it can block active relay link for a brief moment, resulting in packet loss. With a rank-based system, a remote UE can provide ranks to valid relay nodes based on their RSRP values. Now the remote node can establish one-to-one connection with the top two ranking or even three ranking (if necessary) relay nodes. Choosing the relay nodes based on the ranks makes sure the signal quality of backup link is very good. Using ranking system, the remote UE creates multiple links namely primary link and backup links, such that even in the worst case there is always one active link. The multiple link system can also be beneficial to overcome packet loss due to collisions over the sidelinks. The downside of having multiple links is that it uses more resources in the network as the same information is sent twice, hence using twice the number of resources for transmission. Due to this the contenders for resources on sidelink increases and more relays would be occupied. Hence it is important to use a ranking system only for nodes which are in a vulnerable locations to maintain the balance in the network.

Frequency split

Another way to improve the transmission reliability of network can be by using frequency diversity where the frequency for sidelink communication can be different from the frequency for uplink/-downlink communication. This way the collisions due to the UL and SL can be controlled as both the links would be using completely different resources of the spectrum. To use frequency diversity in the network one needs UEs that support communication via dual frequencies with full-duplex capabilities, and there should not be any switching in the frequency. The availability of such UEs is limited.

Dedicated resources

ProSe makes extensive use of resource pools where it dedicates resources for control, data, discovery and synchronization of the relaying network. Similarly, a clear boundary can be created for the resources that can be used for transitional cellular networks and resources that can be used for ProSe by defining the corresponding resource pools. Resource pools can be created for different types of messages that would be transmitted, for example in a factory environment there can be emergency messages. Where emergency messages are mostly of the type URLLC hence for them collision due to sharing of resources can not be an option. In such case, we can have a dedicated resource pool for URLLC messages, such that the messages can be sent using resources from this pool as soon as they are created.

Another important aspect of reliability is choosing the relay UE for communicating with the network. The selection of an ideal relay node plays a key role to improve the transmission reliability. In the next section, we focus on relay selection and what an ideal selection algorithm should do.

4.4.6 Relay selection

In the section 4.3 we discussed what could be a good metric for relay selection and we decided to choose position and RSRP as metric for relay selection. The remote UE needs to choose a relay UE which not only has a strong link with itself but also has a strong link with the base station because if the relay UE does not have a strong link with the base station then it might lose the data or it needs to send the data to another UE which might increase the hops for the packets leading to increase in latency. Hence relay selection is very crucial and it is essential to develop an algorithm to make sure the best relay node is selected for relaying.

What the algorithm should do?

As discussed in the sections before the metric of relay selection consists of three parameters:

1. Position of UEs: Position of UEs is important to make sure the remote UE always connects to the node which is near to it.

2. RSRP of the relay node: With this parameter, we check for the link quality of the relay UE and the base station.

3. Sidelink RSRP: This parameter is used to check for the link quality of remote UE and relay UE.

Considering the above metric the ideal relay selection algorithm should ensure the following:

1. The remote node should select the relay node with the best signal quality with itself and even the base station.

2. The selected relay should ensure the number of hops needed to deliver the packet to its destination is minimum.

3. The selected relay should avoid waiting of messages in queues, as it might add more latency.

4. There are limited resources allotted for sidelink, hence the algorithm should ensure the traffic on sidelink is minimum to avoid collision.

The ideal relay selection algorithm should satisfy the above points to improve the transmission reliability of the network while meeting the latency requirements which is normally critical in relay based communication. Further in this report, we would focus on the implementation of all the design parameters with their choices and features of ProSe applicable to our proposed model. The next chapter would provide an insight into the simulation setup for the proposed model, after which we would look at the implementation of our proposed model with defined simulation parameters.

Chapter 5

Implementation

5.1 Simulation setup

To observe the behaviour of our proposed relaying network we develop a simulated environment of the proposed factory model. The simulated environment would help us observe the behaviour of our network with all the design choices made in the Section 4.3. To develop a simulated environment, we would use a discreet event-based simulator called Ns-3. Ns-3 is a open-source simulator with a very good user and development community. For this project, we extend the ns-3 based proximity service module developed by a team at National Institute of Standards and Technology [35]. The module initially supported only D2D communications, where the UE-network relaying was added in April 2020 (release 3). Hence, the module supports ProSe based UE-to-Network Relay functionality based on 3GPP release 13. The modules provides basic functionalities for UE-to-network relaying but it is developed only for LTE module in ns-3. Further in this section we would explore the simulation parameters used to develop the proposed factory model.

5.1.1 Communication parameters

The communication parameters of the network are stated in the table 5.1, these parameters are based on the design choices mentioned in the section 4.3. In the simulator, we have tried to

Network Layout	
Factory Dimension	50 m x 50 m x 6 m
Number of Base stations (BS):	1
Number of UEs	100
UE distribution	Uniform
UE mobility	3 m/s
General Parameters	
Frequency	800 MHz
Bandwidth	20 MHz
Modulation Scheme	Adaptive
Transmit Power (BS)	27 dBm/50MHz
Transmit Power (UE)	<20 dBm/50MHz
Channel model	Hybrid 3GPP building propagation model (indoor)

Table 5.1: Communication parameters for simulations

replicate the proposed factory model with 80 relay UEs and 20 remote UEs. With one base station positioned at the centre of the factory. The relay UEs are distributed in the network uniformly. The chosen frequency and bandwidth are based on the LTE network, in general, higher bandwidth has more resources which promise better network quality but in a LTE module of ns-3

20 MHz is the highest choice of bandwidth. The transmit power for the networks is chosen as per the Dutch standards.

5.1.2 Traffic model

For the proposed factory network we consider two types of messages which are stated in the table 5.2. The position messages are closed control messages and they are periodic, with these messages

Traffic Model	
Type of message	Periodic
Size of Messages	250 bytes
Message Periodicity	0.5 s
Direction	Downlink and Uplink
Traffic Model	
Type of message	Aperiodic messages
Size of Messages	40 bytes
Message Periodicity	1
Direction	Downlink

Table 5.2: Traffic model

the mobile nodes send their current location to the base station. The other type of messages are aperiodic messages and these are sent by the base station to one or more UEs as control messages.

In this section, we have defined the simulated communication parameters and traffic model that have been used to set up the simulator. After setting up the simulation environment we can observe the behaviour of various ProSe based relaying network campaigns. Further, in the next section, we would discuss the implementation of the relaying network in the simulator, as per the design choices we have made in the previous sections.

5.2 Implementation of UE-to-network relaying

To implement cellular-based UE-to-network relaying, we have extended the ns-3 ProSe module as mentioned in the previous section. The parameters for ProSe are configured according to the discussion in 4.4.4. Additionally, the periodicity of parameters that use the UL to send system information has been reduced to create more space for SL communication. For UE-to-network relaying, relay selection and length of sidelink period plays a critical part of the implementation. Hence, in this section, we would discuss the noticeable implementations that enable the selection of a good relay and provides better system performances. Further, we would discuss the implementation of the relay selection algorithm.

5.2.1 Implementation of shorter sidelink periods

In the Section 4.3, we discussed the the importance of choosing a shorter sidelink period to achieve better network performance. In the figure 5.1 one can see the impact of sidelink period on latency. Here, we consider two active UE-to-network relay links and observe the latency of the network with increase in sidelink period. To see the effects of shorter periods three new subframes period (SF12, SF16 and SF20) were developed and added to the existing ns-3 ProSe module, where SF12 means the period is 12 subframe long and the same implies for SF16 and SF20.

In the figure, the proportional increase in the latency according to the increase of the sidelink period can be observed. Hence, to meet the stringent latency requirement it is necessary to use the lowest possible subframe period, which is SF12. For ProSe a sidelink period should be long enough to support at least two transmissions, where each transmission needs two subframes for

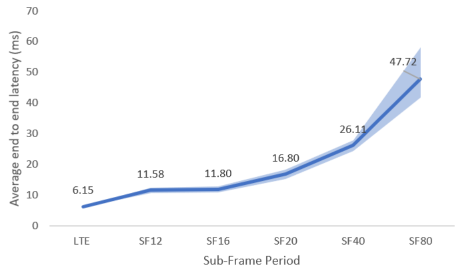


Figure 5.1: Impact of sidelink period on latency

PSCCH and four subframes for PSSCH [35]. Hence the shortest period length for sidelink can be SF12 (12 subframes).

5.2.2 Implementation towards the selection algorithm

Before the implementation of the relay selection algorithms, we would take a look at the implementations that enable the selection of relay nodes and improve the performance of the network. The implementations are mentioned as follows:

1. **Nodes able to provide relaying services:** In our proposed model we consider all static nodes as relay nodes but all static nodes are not providing relaying services. As mentioned in the previous sections, the link between the relay node and the base station must be as good as the link between the remote UE and the relay UE. To ensure only the best relay nodes provide relaying services, the relay UE constantly monitor the RSRP value to determine it's link quality with the base station. If the RSRP value is higher than the threshold than it provides relaying service and if the value is lower than the threshold then it stops it's service as a relay UE.

2. **Choosing relay services**: A remote UE can choose if it wants to relay the data to the network or wants to send the data directly. The relay services for a remote UE starts only when the link quality (which is determined by RSRP) is poor. Similarly, if the direct link quality improves over time then the remote UE stops using the relay services. This way the SL resources are only allotted to the nodes which have a bad link.

3. **Choosing a relay node**: The remote UE tends to select the relay node that has the best link quality with itself. The link quality is determined by the sidelink RSRP values, but the remote UE is mobile and the link quality with a relay UE can change. Hence, the remote UE can select a new relay node or stay connected to the attach relay UE. The decision is made as per the choice of selection algorithms which will be discussed later in this section.

The ns-3 module provides basic functionality for UE-to-network relay but there are some limitations which are the following:

1. The module is developed for LTE, which limits the choice of bandwidth resulting in limited resources.

2. Only one transmission/receiving pool is supported per UE, so the UE can not have multiple pools for various types of messages.

3. Implemented scheduler for relaying is round-robin.

4. Frequency diversity is not supported, the possibility of a UE supporting multiple frequencies is not supported.

5. The module is not designed for IoT applications, which makes it difficult to implement or design a blocking model for a small area like a factory.

We have discussed the implementation and the limitation of the simulation environment which enables us to determine the methods that can be used to improve the transmission reliability of the network. Further, we would discuss the implementation of the selection algorithm.

5.2.3 Implementation of relay selection algorithm

Relay selection algorithm plays a crucial role in developing UE-to-network relaying, the selection of the relay node has a direct impact on the reliability and the latency of the network. It is important for a remote node to select a relay node which can provide minimum hops for communication and also improve the performance of the network. The figure 5.2 shows the basic flow for relay selection algorithm, the threshold value for selection algorithms are based on the values in the table 4.1. In the figure, the red blocks depict characteristics that would depend on different algorithms. For relay selections we consider three different algorithms which are as follows:

1. **MaxRSRP**: In this algorithm, the remote UE selects the relay UE with the maximum sidelink RSRP value from the list of candidate relays. Further, this algorithm supports re-selection, and the remote UE switches the relay node as soon as it finds a relay UE with a better sidelink RSRP value.

2. **MaxRSRPNoReselection**: This algorithm works similarly as the MAXRSRP but it does not support re-selection of relay UE. With this algorithm, the remote UE is connected to the relay until it moves further and is disconnected.

3. **HybridRSRP**: The hybrid algorithm is a combination of the above two algorithms where it selects the relay node with the maximum sidelink RSRP value but for re-selection, it monitors the link quality of established link and decides to switch only if the quality of the link drops below a threshold. This algorithms also makes sure that a relay UE is connected only to one remote UE, unlike other algorithms. Choosing one remote node per relay node is beneficial as this would reduce the load on a relay node and avoid message queuing for multiple remote nodes. However, if the number of remote nodes is greater than the number of valid candidate relays than the algorithm allows a relay node to connect to multiple relay nodes.

All the selection algorithms have their pros and cons, the impact of these algorithms will be observed in the next chapter. In this chapter, we have analysed how relaying can be useful for the described problem statement. We even discussed how relaying can be implemented in cellular networks and made the necessary design choices that would be important to develop a network with improved transmission reliability. Further in this chapter we also described the simulation setup, it's parameters and the implementation of our proposed model. In the next chapter, we would see the behaviour of the proposed network based on the choices made in this chapter by running various simulation campaigns.

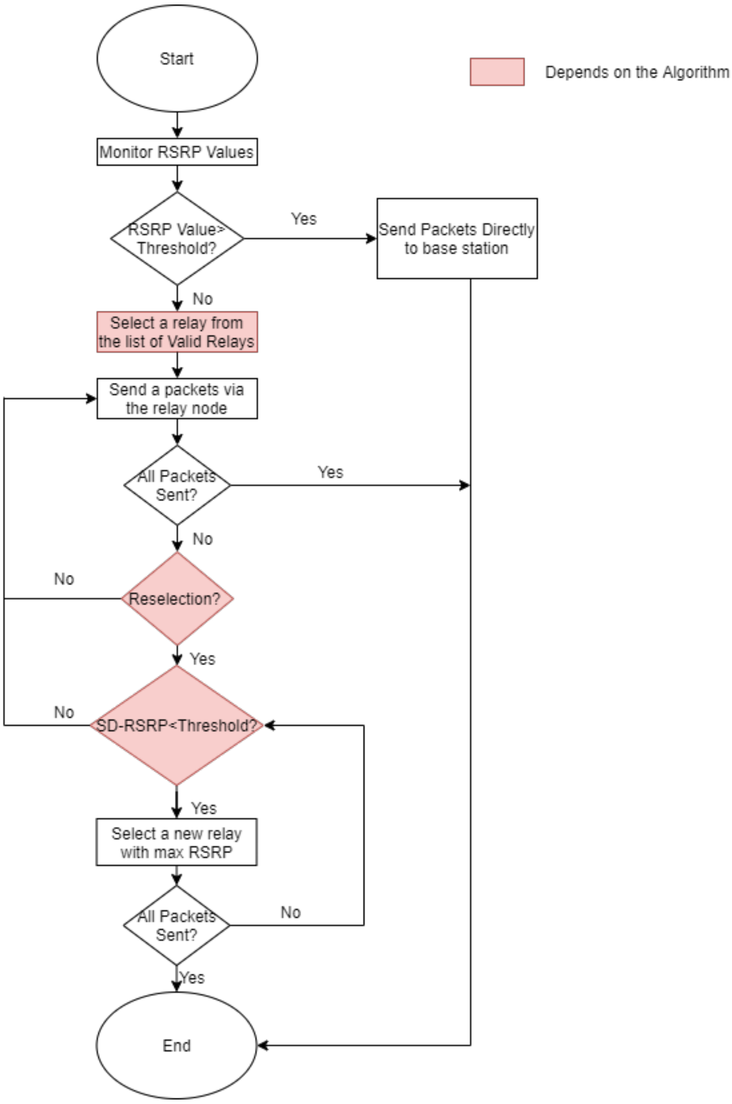


Figure 5.2: Flowchart for relay selection

Chapter 6

Results

In this chapter, we will investigate the behaviour of UE-to-networks relays in a simulated environment of our proposed model. We will run different simulation campaigns to determine the impact of relaying on our proposed factory model.

6.1 Methodology

To achieve robust results, we run the simulations multiple times with different run values such that with every run the initial position of remote UEs are different. Using multiple runs we can simulate the positions of remote UEs such that it covers all the locations in the factory. Additionally, for all the simulation values the mean and 95% confidence interval are shown. Further in this chapter, we would discuss the simulation campaigns in detail.

6.2 Relay selection

In this campaign we will evaluate the relay selection metric. The simulation results are based on a LTE network without the implementation of ProSe. The figure 6.1 shows the variation of RSRP values for 3 UEs with time, the graph is based on the simulation parameters stated in 5.1. The figure shows the RSRP values for one mobile node 97 (blue) and 2 static nodes node 28 (orange) and 66 (green) respectively. The simulation time is 90 seconds and it shows bad signal quality due to concrete block between 30 seconds to 50 seconds. The red circles show the choice of

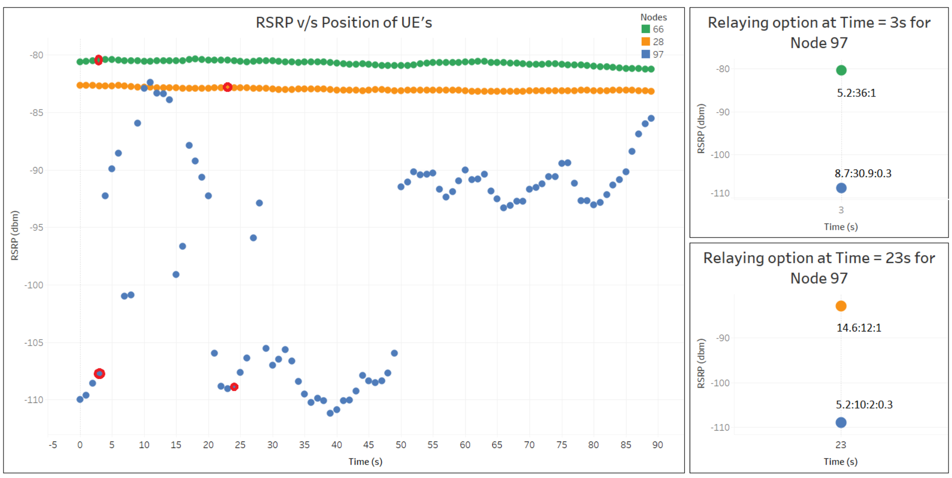


Figure 6.1: RSRP variation with the position of the node

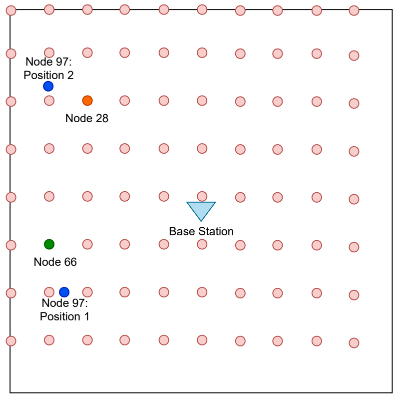


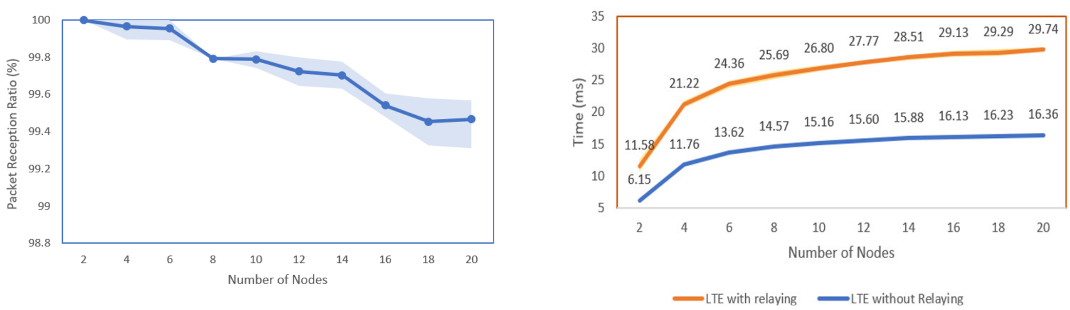
Figure 6.2: Mobility of Node 97 on position 1

relay selection as per the position of the mobile node and their corresponding RSRP values. For example, at 3 seconds the RSRP value of the mobile node is -108 dBm and its position is (8.7, 30.9, 0.3) meters and the position of static node 66 is (5.2, 36.0, 1) meters with the RSRP value of -80 dBm. The positions of the static nodes and mobile node can be seen in figure 6.2. In this case, the mobile node can simply choose the static node 66 as the relay node to communicate to the base station. Similarly, at 23 seconds the mobile node can choose static node 28 as the relay node to communicate with the base station.

The figure shows RSRP values and position of the UEs are a good metric for relay selection, as it can help the remote UEs sense the signal quality and even locate the nearby relaying UEs. This metric helps to reduce the distance and increase the link quality for communication, which would help to improve the reliability of the network.

6.3 Number of remote UEs

In this simulation campaign, we have made sure all the remote UEs present in the network would use relaying services by default. The results in this campaign show the effect of traffic on packet reception rate and average end to end latency of the network. The results show the performance for the whole network, including the position messages and emergency messages.



(a) Packet reception rate

(b) Average end to end latency

Figure 6.3: Impact of change in number of nodes

The figure 6.3a illustrates, as the number of remote UE increases the packet reception rate drops. Drop can be observed due to the increase of collisions over the various links (sidelink and uplink). Initially, when the number of nodes is less, the packet reception rate is 100 % which gradually decreases to 99.466 per cent when the number of nodes increases to 20. We also have to consider that simulation is based on LTE parameters where the maximum achievable packet reception rate for 20 nodes in ideal conditions is 99.666 %. To overcome the effect of packet drop due to collision, a scheduler is needed which can schedule packets within the SLs and even between SL and UL. Developing a scheduler for UE-to-network relays can be an extension of this project.

In figure 6.3b, we can observe the latency of the network rises as the number of nodes increases. The figure shows the average end to end latency comparison of LTE network without relaying and LTE network with relaying. From the figure, one can see the trend in both scenarios is the same. Where the average end to end latency for relaying is the addition of LTE latency (the relay nodes would still use LTE to send data to the base station) plus the control plane latency for relaying, hence the latency with relaying is almost double the latency of LTE network without relaying. The reason due to which the latency is added in relaying are as follows:

1. A packet is not transmitted immediately but it is scheduled to be transmitted on available resources in the next SL period [2].

2. Control channel of sidelink.

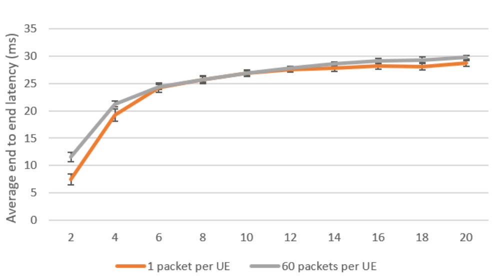
3. In the module, there is a predefined delay of 4 ms between the Medium access layer and the physical layer as defined by the LTE standard. This delay is doubled up in relaying as the packet travels through these layers twice, once for relaying node and once for the base station.

4. The implemented scheduler is a basic round-robin scheduler, hence if there are multiple SL links then each of them are severed periodically.

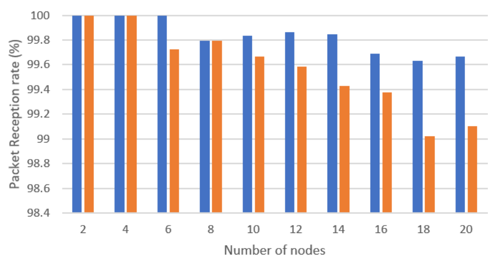
Hence choosing smaller sidelink period is important as seen in figure 5.1. The average end to end latency for 20 nodes is 29.74 ms when the period is SF12 but if we increase the period to SF40 for the same configuration the latency doubles up to 63.33 ms.

In general the average end to end latency and packet reception rate (almost 100%) for aperiodic messages is better than the periodic message due to its small size. However, the average end to end latency for these messages is reduced by just 2 ms than the overall average latency, this instigates us to explore the effects of traffic on the sidelinks.

In figure 6.4a, one can see the impact of control latency. The increase in data packets per node has minimal impact on the average end-to-end latency. We can see the behaviour of the network when each remote UE sends only one packet and when each remote UE sends 60 packets. Initially, when the number nodes is less we observe a significant difference but as the number of nodes increases the latency due to the traffic equalises and eventually, there is a slight increase of 1 ms when 20 nodes send 60 packets each. From this, we can observe the impact of control latency where the time to set up the nodes has a significant impact on latency irrespective of the traffic of the UEs.



(a) Impact of traffic on latency



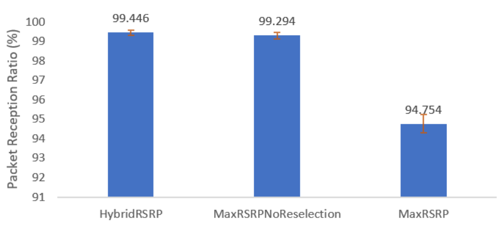
(b) Percentile packet reception rate

Figure 6.4b depicts the 10th and 90th percentile packet reception rate. The 10th percentile means that 10 % of the users would be having a lower packet reception rate than 10th percentile. Hence, we can consider 10th percentile as the worst case and 90th percentile as the best case. The difference between the best case and the worst gradually increases as the number of nodes increases. The results for 20 nodes is interesting, as 90 % of users achieve the same packet reception rate as in the LTE network with no blocking model. This is interesting, as with sidelink the network adds the probability of collision between SLs or even SL and UL, but that has no impact on 90 % of the users. This clearly shows the major issue due to relaying is not packet reception rate but rather the latency added due to relaying.

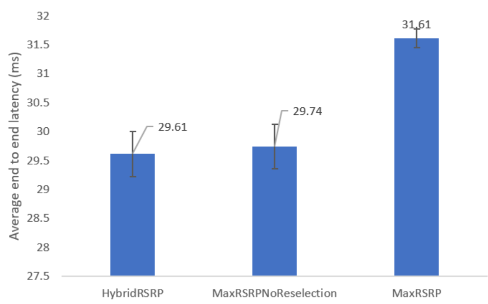
6.4 Selection algorithms

In this simulation campaign, we take a look at the various relay selection algorithm namely MaxRSRP, MaxRSRPNoReselection and HybridRSRP mentioned in Section 5.2.3. We will observe the performance of different selection algorithms for the same network configuration. Figure 6.5 shows the packet reception rate and average end-to-end latency of different relay selection algorithm. When the network performs relaying, it has three options for selection algorithm, out of which the hybridRSRP performs better than the rest with the packet reception rate of 99.446 % as seen in figure 6.5a. The packet reception rate of maxRSRP is the lowest due to the constant switching (approximately 5 switches per node) for the best link. Whereas the difference between the hybridRSRP and MaxRSRPNoReselection is negligible as in these cases the remote node only switches when it is necessary. In hybridRSRP (maximum 2 switches and only for few nodes) the possibility of collision due to switching reduces as less number of nodes are switching, which reduces the signalling messages in the network. Whereas with no re-selection the link is still active with same relay node even when the link quality is bad. This results in more packet loss which accounts for the difference of 0.2 %.

In figure 6.5b, we observe the same behavior as the packet reception rate where the packets are lost due to switching which increases the delay due to re-transmission for MaxRSRP. Additionally in the MaxRSRP and MaxRSRPNoreselection there can be an increase in delay due to the fact that the relay node can handle more than one remote UE. For instance, with MaxRSRPNoreselection there are 2 relay UEs relaying information for 3 remote UEs, but as we can see, the impact due to the round robin scheduler is marginal. Whereas with the HybridRSRP algorithm there is no latency due to queuing as each relay UE has at most one remote UE attached to it. From the results we can observe that the impact on the latency of the round robin scheduler for SL is negligible.



(a) Packet reception rate



(b) Average end to end latency

Figure 6.5: Relay selection algorithms

The figure 6.6 shows the 10th and 90th percentile of packet reception rate for the selection algorithms. One can observe the worst 10 % users and 90 % users of HybridRSRP and MaxRSRPNoreselection have a very small difference. Whereas, for MaxRSRP the difference is almost double, the major cause for this is switching. The worst 10 % users are switching for the best relay link connection more often than the others. In one of the worst case, the node is switching it's relay node at least 7 times in a simulation. It is important to note, when the node switches its relay node, it has to repeat all the signalling steps from discovery and selection as mention in

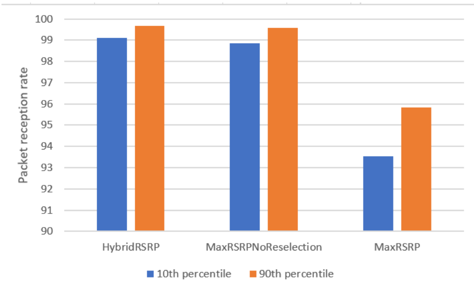


Figure 6.6: Percentile packet reception rate

Section 4.5, to establish a new link. Where in sidelink, control channel is given the priority over the shared channel, hence while switching if there is a collision then the shared channel carrying the packet is always dropped.

6.5 Ranking system with multiple links

With the current module of ns-3 the implementation of a ranking system with multiple links is difficult as the remote UEs have to maintain an active link with two UEs at the same time. To successfully implement that one has to modify the physical and medium access layers of the LTE specifications, which is not in the scope of this project. Nevertheless, we are aware of the increase in traffic due to the data duplication and the ranking system, hence we can observe the effect of traffic on the average end-to-end latency. To see the effect, we tried to make duplicates of the existing remote UEs such that two UEs have the same positions and using the HybridRSRP selection algorithm both UEs would select a different relay node. Doing this replicates the behaviour of a ranking system where one UE selects two links for its communication. From the results in figure 6.7, we can get an idea of how the traffic of ranking system would affect the latency of the network. Compared to the behaviour of the proposed relaying system, for ranking system the average end to end latency increases by 2 ms for sending the same data twice, but the transmission reliability of the network would improve.

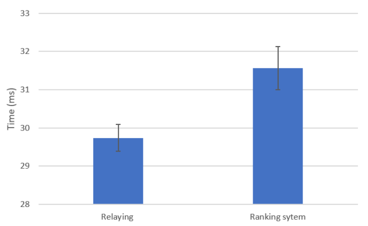


Figure 6.7: Effects on latency due to ranking system

Ideally, with the ranking system the transmission reliability would be promising as for both the links (primary and backup) the remote UE selects the best relay node. Hence the probability to lose a packet would be very less as the same packet is sent twice with two good links. Additionally, it is important to consider that with ranking system the number of resources used are twice whereas the number of resources available for sidelink communications are limited. Accordingly, it is necessary to implement ranking services only for critically located nodes and not all the nodes who are using relaying services.

To see the impact on packet reception rate, we assume there is 10% packet loss due to blocking in factories, which means for every 10 packets 1 packet is lost via the direct link. This would reduce the packet reception rate of LTE network to 90%. Now in the ranking system we consider two links and the packet loss for both the links would be 0.1 each. So the probability of losing a packet with 10% blocking would be 0.1 (for 1st link) × 0.1 (for 2nd link) as both links are used to send the packets. Hence the probability of losing a packet would 1 in 100, which would increase the packet reception rate to 99%. The packet reception rate of 99% is under ideal conditions, as the number parameters like resource collision due to increase in traffic, blocking of relay nodes are not considered.

6.6 Dedicated resources for emergency messages

In this campaign, we try to model the effect of dedicated resources for emergency messages which are of type URLLC. As mentioned in the above sections, ProSe have dedicated resource pools for data, control and discovery channels. Similarly, dedicated resource pool for an emergency message, would guarantee available resources for URLLC messages, where they do not have to contend for resources with other types of messages in the network. It is not possible to simulate an environment with a dedicated pool for a particular message type in the current implementation of the ns-3 module. Hence to observe the channel allotment for sidelink period we used the D2D module available in LTE toolbox of MATLAB [26] to simulate the channel on a physical layer. In figure 6.8, we can see a sidelink period with 40 subframes. The blue region represents the control channel which is PSCCH and yellow region represents the data channel (PSSCH). In the image, one can see the resources from resource number 80 to resource number 100 are reserved for emergency messages and can be used to avoid any collisions due to other types of messages. In the figure 20 resources blocks are allocated for emergency messages as in the proposed factory model the size of emergency messages is 40 bytes. In LTE, one resource block can carry 1 emergency message from one UE hence there is a provision for all 20 nodes.

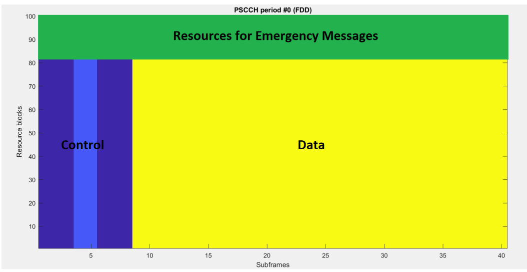


Figure 6.8: Dedicated resources for messages in a sidelink period

To implement the network, one needs to develop an algorithm for resource allocation which makes sure that the resources are always available for emergency messages in a sidelink period. Additionally, the algorithm should be able to send the message immediately after its creation, and this will be the major implementation challenge as it contradicts ProSe standards. In ProSe standards, a message is not sent immediately but in the next period after the control channel allots the resources for communication. Hence the algorithm for URLLC messages should make sure the message is sent immediately via the available resources in a sidelink period to meet the stringent latency requirements. Such an algorithm needs to be developed from the physical layer, which can be interesting for future research.

6.7 Network behaviour

Till now we have seen the results of the network where all the remote UEs are using relaying services but this will be unrealistic in real-life scenario where all the nodes would not have a bad link at the same time and if they do then it would imply the initial design of the network is faulty. Hence in this simulation campaign, we would look at the performance of the network with a practical viewpoint, where the remote UE would only choose to opt for a relay service only in case of a bad link with the base station (determined by the RSRP value in 4.1) and if the link improves than it would switch back to the direct link. In table 6.1 one can see the performance of the network. The end-to-end average latency is dropped by almost 10 ms compared to a network where all the remote UEs are using relaying service, whereas the packet reception is slightly (0.1 %) higher than the scenario where all nodes are using a relay link, this is due the fact that node having a direct link do not add to the collision on the sidelinks. Similarly, the drop in latency is due to the fact that some remote UEs are using a direct link and some remote UEs are using the sidelink, hence the average latency is lowered, as the packet is delivered faster without any hops via the direct link. Munz et al. [30], illustrate how relaying can improve the packet error rate in a factory environment. They consider six different signals and compare the packet error rate of a direct link and the relay link, which can be seen in the figure 6.9. In the figure the first bar shows the direct link and the second bar shows the relay link. Unfortunately, we were not able to implement a blocking model in our simulator as the ns-3 LTE module is not designed to develop simulations for a small area like factories.

Packet Reception rate	Average end to end latency
99.50%	20.30 ms

Table 6.1: Realistic network behaviour

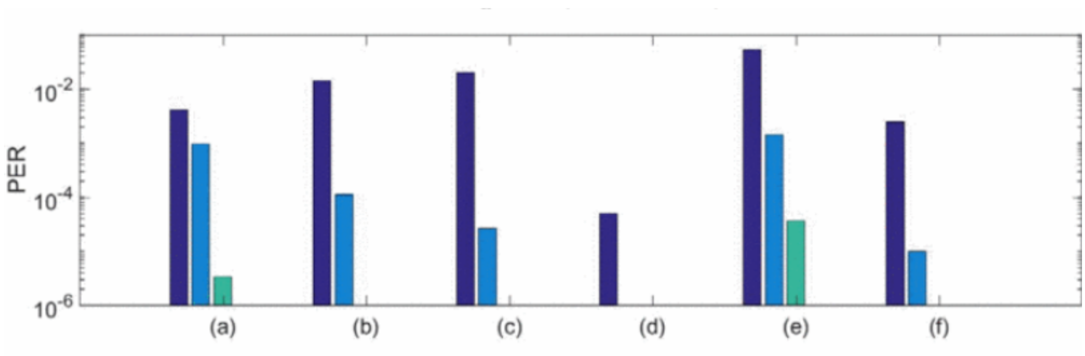
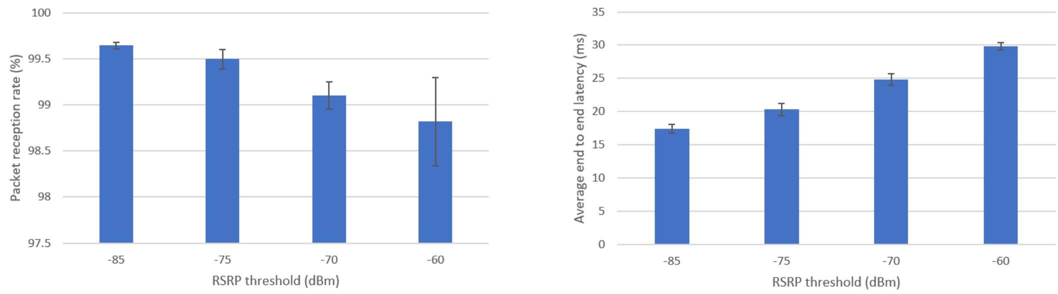


Figure 6.9: Packet error rate comparison of direct link and relay link [30]

Nevertheless, we have tried to create a worst-case environment for the factories where we have predefined additional losses for the simulated model. The worst case environment, helps us to see how relaying would help compared to the direct LTE link. Additionally, we would see the impact of RSRP thresholds on the network. Ideally, if we decrease the threshold for relaying services, then the number of relay nodes providing relay services will decrease. Whereas if we reduce the threshold for remote node using relaying services, then more number of nodes would be using relaying service. The ideal behaviour with good signal conditions can be seen in the figure 6.10, where one can observe the packet reception ratio 6.10a and delay 6.10b are better when less number of nodes use relaying services. This clearly shows that relaying should be used only when the node needs to. Hence the nodes should periodically monitor RSRP values and switch to direct link or relay link during run time. Switching helps to reduce the unnecessary traffic on the sidelink.

In the figure 6.11, we can observe the impact of RSRP thresholds in the worst-case environment compared to the direct link. In the figure we can see the drop of packets in the LTE link due to losses at 97.67% when no relay nodes are involved. When we use relaying services we can tune the RSRP threshold value, which restricts the number of relay nodes that can be used for relaying services. In general, less relay nodes would result in lower latency but in this case even the packet reception rate has decreased. From figure 6.11a, one can observe that threshold decreases the

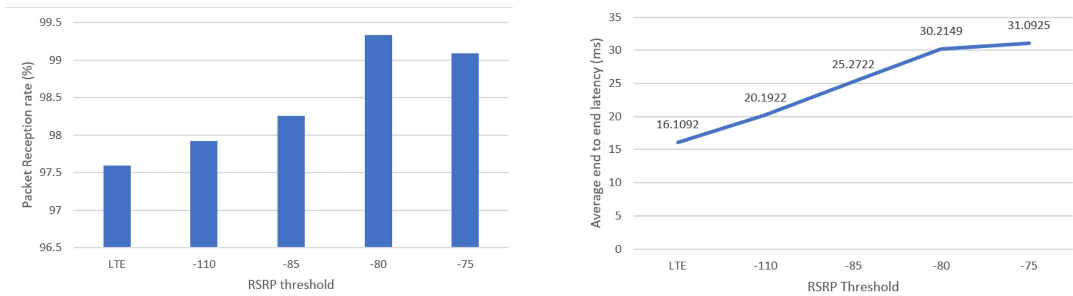


(a) Packet reception rate

(b) Average end to end latency

Figure 6.10: Effects of RSRP threshold

packet reception rate increases which means more number of nodes are using relaying services. One of the major reason for this is due to shorter length of communication. With relaying the remote node selects the a nearby node to send the data, which reduces the length of communication. The impact of losses on shorter routes is less, which increases the packet reception rate. Similarly, in figure 6.11b as the threshold decreases the latency of the network increases. One of the interesting behavior is seen when the RSRP threshold is -75 dbm; the packet reception rate decreases while the latency is increased. This is because the traffic in the network has increased, as all the nodes are using the relaying service, which adds collision due various sidelinks and uplinks. The best result is obtained when the RSRP threshold is -80 dbm in this case 15 nodes are using relaying services and the rest are using the direct link. With 15 nodes the packet reception rate raises by 2% but at the same time latency is doubled. Hence from the results, we can see it is important to use relaying services only for the necessary nodes such that the traffic on the sidelink is maintained. The collision due to traffic can be decreased by providing more resources for sidelink communication and this is possible by using advanced technology like 5G. The benefits of 5G for relaying will be discussed in the next section.



(a) Packet reception rate

(b) Average end to end latency

Figure 6.11: Effects of RSRP threshold on worst case scenario

6.8 Relaying with 5G

Noticeably the simulation results are based on 4G standards of 3GPP release 13 which was proposed in 2016, thereafter 3GPP has proposed new standards and more importantly 5G which is superior to the implemented 4G standards. Some of the important standards for sidelink in 3GPP release 16 are mentioned below:

1. Grant free NR sidelink transmission, which improves the latency of the network.

2. New design for PSCCH to enhance channel sensing and resource selection procedure.
3. Quality of service management is supported in sidelink transmission to overcome congestion control and achieve a high density of connections. This can also help to prioritize URLLC messages.

In general, 5G offers higher bandwidth with would be beneficial for sidelinks as the size of the pool of resources would be larger and the devices would have more options for choosing a resource. As of now implemented 4G module in ns-3 supports maximum bandwidth of 20 MHz which is 100 resources. With 5G, we can use a 100 MHz bandwidth where the available resources are 500 (for 15 kHz subcarrier) which is 5 times higher than 4G. With this increase in the available resources, the probability of collision due to various links can be reduced, if allotted accordingly. Moreover, in 5G standard, there is a possibility to change the numerology of the network such that the length of one subframe can be reduced from 1 ms (as per the 4G standard) to 0.125 ms. Hence reducing the time for the sidelink period of SF12 from 12 ms to 1.5 ms, which can improve the latency of the network drastically. If we assume the latency of the network is 5 ms and we have a subframe period which is of 1.5 ms then the approximate latency of the network would be 5 + 0.75 = 5.75 ms for 2 nodes. We consider the average latency due to subframe to be half the sidelink period, by estimating the average latency due to sidelink period would be half of the sidelink period. This trend is even visible in figure 5.1, where we observe the latency due to sidlink period. Hence, by taking the benefit of numerology in 5G, we can reduce the added latency for SF12 from 6ms to 0.75 ms approximately.

Chapter 7

Conclusions and Recommended Future Scope

To conclude, the simulated relaying network discussed in this project has shown some promising implementation and performance results for factory environments. Our goal was to investigate and design relaying solutions to improve transmission reliability for critical-IoT applications. In light of this, we decided upon the design parameters for implementing relaying network using cellular-based ProSe. We have simulated the designed factory model by extending the existing UE-to-network relay implementation of ns-3, to see the impacts of relaying networks. The simulation results show that cellular-based UE-to-network relaying can be a promising solution for factories of the future, where achieving high reliability would be as challenging as achieving lower latency. The simulation results show that the maximum achievable packet reception rate when all source nodes use relay links is 99.466% (for ideal condition) with an average end-to-end latency of 29.73 ms. Whereas in a practical scenario, where only the nodes with a having a poor signal strength use relaying link, the packet reception rate is almost the same with the average latency dropping by approximately 10 ms. The results show that, it is necessary to use relaying services only in case of bad signals quality. This helps to maintain the minimum traffic on sidelinks and improve the overall network performance.

For critical-IoT application the basic requirement is high reliability. Reliability is dependent on the packet reception rate and latency. For latency, the parameters that has the highest impact on it is the sidelink period. Therefore, developing shorter sidelink periods was a critical part of this project, as shorter periods reduce the latency by almost 20 ms. Another factor causing an increase in latency is a predefined delay that is added to synchronize the medium access layer and the physical layer. This could be an interesting extension of this project to see the impacts of this delay. Furthermore, to improve the network performance we have developed relaying algorithms, which decide the nodes that can use or provide relaying service with relay selection. We have implemented a hybrid algorithm, where the signal quality information is taken from the base station and resources are selected by the nodes. With this algorithm, we make sure that only the best links are used for relaying. This helped us in reducing the number of hops in the system. It also reduced the overhead on the base station for resource allocation.

Relaying solutions are cheap and easy to implement which helps the network to adapt to the flexibility of the future factories. At the beginning of the project, we laid a couple of questions about relaying. These were addressed gradually in our discussion and we are now ready to state the answers:

1. When to do relaying: The remote node should use relay services only when it's link quality is poor, this can be determined by periodically monitoring the RSRP.

2. Which technology to use for relaying: For a factory environment, it would be practical to maintain the uniformity in order to reduce the need for extra infrastructure. Hence, using cellular-based relaying with private cellular network would be a good choice for industry 4.0.
3. Routing: It is essential to choose a route with minimum hops. Using a relay node having a good signal strength with the base station as well as the remote node would ensure packet delivery in one hop.
4. Latency constraints: To meet the latency constrains, firstly the network should be designed with the smallest possible sidelink period. Secondly, the remote node should select the best relay node for communication.

Additionally, we discussed about various methodologies that can be implemented with the relaying algorithm to meet the requirements of URLLC communications. These were:

1. Dedicated resources
2. Frequency split
3. Ranking systems with multiple links

These methodologies have not been implemented in the simulation environment due to limitations of the chosen simulator and the cellular standards.

The objective of this project was to investigate and design a relay-based network for critical applications in a factory environment and we proposed a network design which can be used for the factory, but achieving the stringent latency requirement has not been accomplished in this work. Hence with this paper, we propose some directions for further work:

1. Development of a scheduler to schedule uplink, downlink and sidelink in order to prevent collision among them.
2. Improvement of the control latency: As seen in the results, latency overhead due to control plane is very high. Reducing the control latency would be very beneficial to improve the overall latency of the network.
3. Multiple resource pools: Due to the limitations of the simulator, we have not been able to investigate observe the behaviour of a dedicated pool for URLLC messages. This could be a good topic of research.
4. More sophisticated relay selection: At the moment in this project, a relay is selected as per the RSRP values, but in a factory environment the mobility of the machines are predictable and repetitive. Hence by using advance technologies like machine learning, we can have a better selection and switching algorithm through location-based predictions.
5. Using wired relays: As per the ProSe standard, the uplink and sidelink share the same spectrum. It would be interesting to use some relay nodes which use wired connection reducing the uplink traffic.

List of Acronyms

3GPP 3rd generation partnership project. 10, 11, 18, 30, 33

5G Fifth Generation. 33

AGV Automated Guided Vehicles. 5, 6, 9, 33

AODV ad hoc on-demand distance vector protocol. 3, 33

BS Base Station. 18, 33

D2D device to device. 3, 4, 10–12, 18, 28, 33

dbm decibel milliwatts. 10, 33

DCA Direct communication Accept. 13, 33

DCK Direct communication keepalive. 14, 33

DCKA direct communication keepalive acknowledge. 33

DCR Direct communication request. 13, 33

DL Downlink. 12, 15, 33

DSMCm Direct security mode command. 13, 33

DSMCp Direct security mode complete. 13, 33

DSRC Dedicated Short Radio Communication. 5, 33

FoF Factory of Future. 5, 6, 9, 33

IMSI International Mobile Subscriber Identity. 33

IoT Internet of Things. 1, 20, 33

IP Internet Protocol. 12, 13, 33

LoRa Long Range. 5, 33

LTE Long Term Evolution. 3, 4, 8, 11, 18, 20, 23, 25, 27–29, 33

MHz Megahertz. 19, 33

ProSe proximity services. 4, 11–19, 23, 28, 32, 33

PSCCH Physical Sidelink Control Channel. 14, 20, 28, 33

PSDCH Physical Sidelink Discovery Channel. 14, 33

PSSCH Physical Sidelink Shared Channel. 14, 20, 28, 33

QoS Quality of Service. 5, 33

RAT Radio Access Technology. 8, 33

RE Resource Elements. 10, 33

RRC Radio Resource Control. 13, 33

RS Reference Signals. 10, 33

RSRP Reference Signal Received Power. 10, 11, 16, 17, 20, 21, 23, 29, 30, 32, 33

SL Sidelink. 12, 14–16, 19, 20, 25, 26, 33

TNO The Netherlands Organization for Applied Scientific Research. 1, 33

UE User Equipment. 1, 3, 4, 6, 8, 10–21, 23–29, 33

UL Uplink. 12, 15, 16, 19, 25, 26, 33

URLLC Ultra-Reliable low-latency Communication. 1, 3, 8, 16, 17, 28, 31, 33

V2X Vehicle to everything. 5, 33

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Appendix A

Code implementation in ns-3 simulator

The implementation code can be found in the link below:
https://gitlab.com/aadesh/factory_relaying

The network layout and design configuration are implemented in the `scratch\factory.cc`. In the file location `src/lte/model/` you can find a file name `lte-sl-basic-ue-controller` which has the implementation of relay selection algorithms. One can run these files by downloading ns-3 from https://www.nsnam.org/releases/ns-3-29/download/ and then install the LTE D2D module from urlhttps://apps.nsnam.org/app/publicsafetylte/.

To run the simulation, you need to go to the folder where ns-3 D2D module is installed and run the following command:

```
./waf--runscratch\factory.cc
```

This would start the simulation.