UNIVERSITY of OULU

DEGREE PROGRAMME IN WIRELESS COMMUNICATIONS ENGINEERING

MASTER'S THESIS

ULTRA RELIABLE LOW LATENCY COMMUNICATION IN MTC NETWORK

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ABSTRACT

Internet of things is in progress to build the smart society, and wireless networks are critical enablers for many of its use cases. In this thesis, we present some of the vital concept of diversity and multi-connectivity to achieve ultra-reliability and low latency for machine type wireless communication networks. Diversity is one of the critical factors to deal with fading channel impairments, which in term is a crucial factor to achieve targeted outage probabilities and try to reach out such requirement of five 9's as defined by some standardization bodies. We evaluate an interference-limited network composed of multiple remote radio heads connected to the user equipment. Some of those links are allowed to cooperate, thus reducing interference, or to perform more elaborated strategies such as selection combining or maximal ratio combining. Therefore, we derive their respective closed-form analytical solutions for respective outage probabilities. We provide extensive numerical analysis and discuss the gains of cooperation and multi-connectivity enabled to be a centralized radio access network.

Keywords: 5G, Ultra Reliable Low Latency, Fading Channels, Reliability, Outage Probability, Maximum Ratio Combining, Selection Combining, Signal to Interference Ratio, Machine Type Communication, Multi-connectivity.

TABLE OF CONTENTS

FOREWORD

The focus of this thesis is to study on the Ultra Reliable Low Latency Communication in MTC network. This research was carried out at Centre for wireless communication (CWC) as part of High5 project and was financially supported by Academy of Finland 6Genesis Flagship (grant 318927), Academy of Finland (Aka) (Grants n.303532, n.307492) and by the Finnish Funding Agency for Technology and Innovation (Tekes), Bittium Wireless, Keysight Technologies Finland, Kyynel, MediaTek Wireless, Nokia Solution and Networks. A special thanks to my supervisor Dr. Hirley Alves who always had time to discuss the thesis, very supportive and genuinely interested in my results. I would like to thank Prof. Matti Latva-aho for giving me the opportunity to join the research group in the CWC. I would also like to thank my team mate Mr.Onel L.Alcaraz López who helped with the initial set up and let me guide with simulation work. I would like to thank all my MTC group team member, colleagues and Oulu Nepalainen friends for their encouragement and making my days beautiful throughout this journey.

Special thanks to my parents, brother, sisters and my wife who supported me all the time and above all to God who led me to this achievement.

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Binod Kharel

ABBREVIATIONS AND SYMBOLS

4G	Forth mobile generations
3G	Third mobile generations
2G	Second mobile generations
IP	Internet Protocol
HCC	Human Centric Communication
IoT	Internet of Things
5G	Fifth mobile generations
3GPP	3rd Generation Partnership Project
ITU	International Telecommunication Union
IMT	International Mobile Telecommunications
eMBB	Enhanced Mobile Broadband
mMTC	Massive Machine Type Communications
URLLC	Ultra-Reliable Low Latency Communications
TTI	Transmission Time Interval
MC	Multi Connectivity
JD	Joint Decoding
MRC	Maximum Ratio Combining
SC	Selection Combining
RRH	Remote Radio Head
UE	User Equipment
MAC	Multiple Access Channel
MTC	Machine Type Communication
C-RAN	Cloud Radio Access Network
CU	Central Unit
BBU	Baseband Unit
LTE	Long Term Evolution
LTE-A	Long Term Evolution Advanced
ETSI	European Telecommunication Standards Institute
GPRS	General Packet Radio Services
WCDMA	Wideband Code Division Multiple Access
UMTS	Universal Mobile Telecommunication System
RAN	Radio Access Network
MIMO	Multiple Input Multiple Output
NB-IoT	Narrowband Internet of Things
LPWA	Low power wide area
LAA	Licensed Assisted Access
V2V	Vehicle-to-vehicle communication
V2X	Vehicle-to-everything communication
5D	5G working group
QoS	Quality of Services
NR	New Radio
mmWave	Millimetre wave
D2D	Device-to-Device Communication
M2M	Machine-to-Machine Communication
HTC	Human Type Communication

MNOs	Mobile Network Operators
MVNOs	Mobile Virtual Network Operators
SCMA	Sparse Code Multiple Access
CS-MUD	Compressed Sensing-Multi User Detection
BLE	Blue tooth Low Energy
RPMA	Random Phase Multiple Access
BLER	Block Error Rate
PHY	Physical Layer
e2e	End-to-end
PLC	Process Logic Controller
C	URLLC capacity
L	User plane latency
R	Reliability
X	Fraction of users in outage
Y	No of users
UL	Uplink
DL	Downlink
HARQ	Hybrid Automatic Repeat Request
AI	Artificial Intelligence
NOMA	Non-Orthogonal Multiple Access
LLC	Low latency communication
URC	Ultra reliable communication
LEO	Low Earth Orbit
RAT	Radio Access Technology
AWGN	Additive white Gaussian noise
cMTC	Critical machine type communication
EN	Enhanced node
MTD	Machine type device
η	Total number of RRH
d_0	Distance from typical RRH to user equipment
d_j	Distance from interfering RRH to user equipment
α	Path loss exponent
θ	Threshold in dB
I_j	Interference from j^{th} RRH to user equipment
k	Number of RRH in cooperation
h_0	Channel fading coefficient of typical link
h_j	Channel fading coefficient of interfering links
SIR	Signal-to-interference ratio
$SINR$	Signal-to-interference noise ratio
$\text{Exp}(1)$	Exponential distributed random variable with mean 1
CDF	Cummulative Distribution Function
PDF	Probability density function
ϵ^{th}	Reliability constraints
F_x	Cummulative distribution function
f_x	probability density function of x
Ω	Maximum of SIR in selection combining
$\mathbb{P}$	Probability

${}_2F_1$	Hypergeometric regularized function
Γ	Gamma function
max	Maximum
e	exponential
$\exp$	exponential
P	Random variable
q	Random variable
Z	Random variable
r	Rate of transmission
h_i	Fading channel coefficient of RRHs in cooperation with typical link

1. INTRODUCTION

We firstly describe the background and motivation, thesis contribution which relates evaluation and purpose, proceeding by problem formulation and contribution that aim to answer the following research questions:

- How cooperation and spatial diversity can be used to solve issues of reliability and latency in ultra reliable low latency communication in MTC network?
- What are the way of spatial diversity that would best result with respect to ultra reliable and low latency in MTC network in terms of outage probabilities and reliability?

1.1. Background and motivation

We are just at the beginning of transition into fully connected Networked Society[1] that will provide access to information and sharing of data anywhere and any time for anyone and anything. Thus, in the future wireless access will not only be about connectivity for people but for anything that benefits from being connected[2]. As mentioned in [2], today a large number of devices are connected to the network, mobile phones and computers connected to the internet and many devices like sensors, actuators are connected to the network. We are in the verge of fully connected network society and in transition towards smart society. Large number of devices connected to the network demand for large amount of data and current network could not be sufficient to fulfil these demands. According to Cisco [3], mobile data traffic has increased 18-fold between 2011 and 2016. At the end of 2016, traffic volume per month had reached 7.2 exabytes showing 63% growth in one year. The connection speed has also grown 3-fold. With only a 26% share of mobile subscription, 4th Generation (4G) connection have generated 69% of the mobile traffic-which is four times greater than the traffic generated by 3rd Generation (3G) connections. Cisco[3] also predicts that mobile traffic will increase seven fold between 2016 and 2021, while the speed increase will be three-fold. By 2021, the mobile traffic will reach 49 exabytes per month, accounting for 20% of the total Internet Protocol (IP) traffic.

Based on these forecasts, statistics and scenarios the way of society is changing will lead to changes in the way mobile and wireless communication systems are used. Essential services such as e-banking, e-commerce, e-learning and e-health will continue to proliferate and become more mobile. On-demand information and entertainment (e.g., in the form of augmented reality) will progressively be delivered over mobile and wireless communication systems. These developments will lead to an avalanche of mobile and wireless traffic volume to increase a thousand fold over the next decade[3][4]. In future, the prediction is that there will not only the Human Centric Communication scenarios but be complemented by tremendous increase in the number of communicating machines. This is so-called Internet of Things will make our everyday life more efficient, comfortable and safe. There are forecast of total of 50 billion connected devices by 2020[1][4]. This increasing demand of data rate in different areas and different scenarios evinces that a new mobile network is in progress, developed and is being standardized. This mobile network is called 5th Generation (5G). The standardization process is going on and performed by 3rd Generation Partnership Project (3GPP) and the International Telecommunication Union (ITU). The ITU have not specified the requirements for 5G mobile network, but have released a report called "Framework and overall objectives of the future development of IMT for 2020 and beyond"[5]. This report focused on the ITU's vision for the 5G society and is used as framework to develop the requirements for 5G. The report identified and proposed the three usage scenarios to support a diverse range of application that will be a part of upcoming 5G standard. The scenarios are:

- Enhanced mobile broadband (eMBB): more throughput, referring to application such as video streaming, on-line gaming and virtual reality which need high BW data access.
- Massive machine type communication (mMTC): more connected devices, expected connection of billion of devices to the internet.
- Ultra-reliable and low latency communication (uRLLC): more reliability, concerned with application such as automation and vehicle to vehicle communication that demand reliability of five 9's 99.999%.

In this context, this work addresses issues related URLLC, where reliability and low latency are more relevant than throughput. High reliability is the process of receiving data and decoding a packet of data correctly with very high probability. Latency is the time duration transmitter decides to send data to the receiver receives the data and it is successfully decoded.

To meet the ultimate demand of high reliability, diversity methods that combat channel fading impairments are to be exploited even further in future wireless networks. The use of diversity both in frequency, time and space can be deployed. Diversity is a method to improve a reliability by transmitting a packet over multiple channels and combining the received packet into one more reliable packet. The reliability is assured here as transmitting a packet over multiple channels compromise with the fact that if one channel goes under dip fade then other channels can compensate the loss as different channel undergoes different level of fading. Spatial diversity is a special case of antenna diversity or space diversity where different antenna can be used in transmission forming different channel in space domain. Such gains, can be achieved via spatial diversity (multiple antennas at transmitter and/or receiver and cooperative schemes for instance). Time diversity is difficult to exploit due to the targeted very low latency, otherwise, the message could be repeated to achieve a higher reliability. In order to ensure lower latency the Transmission Time Interval (TIT), duration of transmission over radio interface can be shortened[6].

Such diversity mechanism are a good way to enhance reliability and latency so to cope with emerging applications scenarios in the context URLLC such as mission critical industrial automation or communications for vehicular coordination which require an extremely high reliability (e.g., frame error rates of 10^{-9}) while simultaneously providing low latency (e.g.,1 ms end to end delay)[7]. These scenarios requires trade off between both reliability and low latency while other scenarios trade-off either reliability or latency.

Multi-connectivity (MC) is seen as a promising concept to enable URLLC in 5G by establishing multiple diversity branches in the frequency domain. Different combining algorithms are known to take advantage of multiple diversity branches like Joint decoding (JD), Maximum Ratio Combining (MRC), Selection Combining (SC)[8].

We assume that different Remote Radio Head (RRH) equipped with the single antenna are connected to the user equipment (UE) and form a special case of multi-connectivity or spatial diversity. The multiple diversity branches that corresponds to an orthogonal multiple access channel (MAC) are realized by different carrier frequencies. Thus, the information can, in the best case, be delivered in a single time slot, which helps satisfying the URLLC requirements[9]. However, multiple connections can also be utilized to enhance the reliability i.e the same information is transmitted over all branches in parallel[10].

Diversity can be considered as key enabler of URLLC in MTC network which in term is the enabler of different critical IoT services. In the case of multi-cell deployment to enable the critical MTC network applications, such as factory automation two options could be considered as mentioned in[11].

- Frequency planning and coordination where the cells may use at least partially separate frequencies,

- Frequency reuse where neighbouring cells fully operate on the same frequency bands or resources.

These planning are also major factor to limit the interference in the given area to enable any MTC network in a given area which is also necessary to maintain the reliable coverage within the area and minimum threshold to maintain diversity order.

This is possible today because we envision the use of C-RAN and virtualization in the network. The C-RAN architectures offers the possibility to move the baseband unit (BBU), to Central Unit (CU), in support of multiple Remote Radio Head (RRHs). The split could be pre-defined for different network slice, or it can be dynamically changed for different types of traffic or depending on the network conditions, which could be configured via top-level network controller and offered as a service[12],[13].

1.2. Thesis contribution

This master's thesis proposes and evaluates methods of spatial diversity in 5G to better fits the need of URLLC. The aim is to provide guidelines on how spatial diversity can be implemented for URLLC and get insights into what benefits emerge when user equipments are connected with multiple RRHs and different combining techniques are performed.

In the thesis, we evaluate a MTC network with URLLC requirements (as in a factory automation settings) where a MTC device equipped with single antenna is connected with multiple RRHs where each RRH's is equipped with single antenna in the given area and considered as a point to point link. In the work, RRHs are connected to the cloud link where Baseband Unit is present in cloud using cloud server, we are proposing to establish a reliable and latency aware wireless communication access layer model.

Different from [14] our work is mainly based on assuming interfering base station in a given area are in equidistant from the UE and the basis of our system model assumptions are mainly based on [7],[9],[10]. Conversely, we are enabling cloud link scenario which has capabilities of processing data at the edge of network enabling edge computing scenario compensating the latency constraints.

In the work it is hard to realize exactly how many RRHs should be incorporate or what will be the threshold of received Signal-to-interference-ratio or where to place the base station. To evaluate these constraints we have proposed $(k - out - N)$ strategies along with the combining algorithms like Selection Combining and Maximum Ratio Combining with cooperation strategies. Considering distance analysis we have proposed the scheme with one typical link close to UE and other interfering links are far from concerned reference link to cope interference.

Therefore, all the parameters in consideration of link distances, threshold and reliability we have derived a closed analytical solution to different proposed combining strategies and the problem are analysed and discussed with their corresponding analytical and simulated solution. Therefore, a thorough study that simulates all the parameters and give out the best result in context of targeted outage probabilities is carried out in the thesis.

1.3. Outline of thesis

Herein, we give the reader a clear outlook of the remaining of the thesis organization as follows:

- **Chapter 2:** consist of the necessary theoretical background and state of art of radio access technologies for machine type communication and ultra reliable low latency communication.
- **Chapter 3:** provides the detailed of work carried out, network scenario, a system model which are necessary to answer research question. Herein, we provide detail derivations and the closed-form expression for the propose problem. We evaluate several scenarios and compare their performance in terms of reliability.
- **Chapter 4:** presents the numerical results and discussion. Moreover, we provide several numerical examples of the performance of the schemes under analysis, and our analytical results are corroborated via Monte Carlo simulations.
- **Chapter 5:** this chapter consist conclusion section which provide summary to the formulated problem and present ideas for future work.

2. THEORETICAL BACKGROUND

This chapter presents the theoretical background of the thesis covering State-of-art Radio Access Technologies like LTE, LTE advance, LTE pro and 5G. Along the thesis fundamental of MTC and URLLC as indispensable use for coming 5G networks are also the backbone of the thesis. We elaborate the key theoretical concepts about the thesis and present methodology.

2.1. State-of-the-art Radio Access Technologies

Cellular technologies from its early stage of analog communication to present day high-speed internet has gone tremendous changes to incorporate the society providing services and application to billion of users worldwide. GSM was the first global standard developed by the European Telecommunication Standards Institute (ETSI) as the 2nd Generation(2G) mobile technology[15]. Time after time, the diverse requirement of cellular technologies has been constantly growing and demanded technology around the globe. 2G mobile networks were mainly used for voice communication where services, coverages and capacity requirements where the main concerned issues, and later on, ETSI introduced packet switch access in the General Packet Radio Services (GPRS) standard [16], which is sometimes referred as 2.5G standard. After the development of the internet over cellular technologies there has been an exponential growth in demand of data. 3G was introduced by 3GPP as a broadband access technology using wideband code division multiple access (WCDMA) as air interface and was referred as Universal Mobile Telecommunication system (UMTS)[17]. UMTS was followed by LTE and LTE continues to evolve with LTE-A, LTE-A pro, which is the foundation laystone for 4G mobile technology[18]. With the success of LTE, 3GPP is laying foundation stone towards 5G. Next, we describe the state-of-art RAT, 5G and the requirements for the future 5G use cases.

2.1.1. 5G

5G refers to the term fifth generation of mobile networks standard that will go beyond current IMT advanced capabilities. According to ITU-R[19] 5G is expected to meet diverse requirements and capabilities by 2020. Three main usage scenarios and verticals of 5G that were identified are namely eMBB, mMTC, URLLC. The summary of diverse requirements and key parameter is given in Figure 2.1.

The eMBB is related to the high data rate and unique user experience like video streaming, online gaming and virtual reality focusing basically on human-centric applications. The key performance indicators are data rate, spectrum efficiency, mobility, area traffic efficiency and network energy efficiency. The key technical parameters are peak data rate upto 20 Gbps, user experienced data rate of 100 Mbps, peak spectral efficiency 30 bps/Hz and mobility of 500 Km/h and three times more spectral efficiency compared to IMT-advanced without increasing energy consumption.

The mMTC covers the scenarios of large densely connected devices which are used for a specific purpose and are expected to transmit rarely a few bytes of data. mMTC

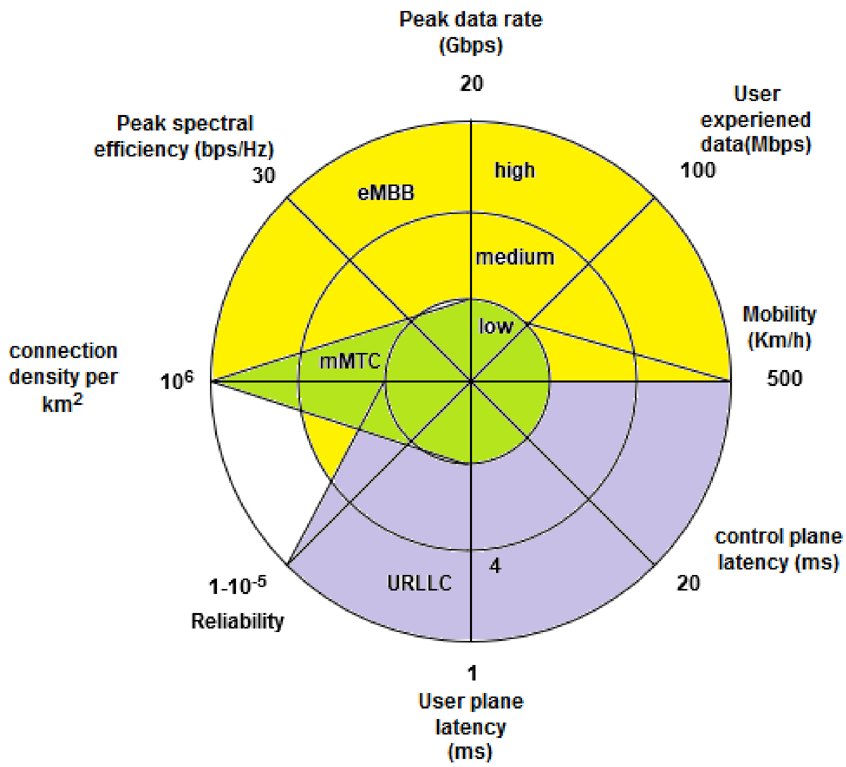

Figure 2.1: The key minimum technical requirements for 5G use cases.

key technical parameters are connection density of 1 million per km^2 and with low data rate.

While, URLLC covers the scenarios that require high reliability and low latency e.g., applications like factory automation, vehicle-to-vehicle communication (V2V) and V2X (vehicle-to-everything). The key technical parameters required for these use cases are reliability is beyond $1 - 10^{-5}$, user plane latency as low as 1 ms with low data rate and about 4 ms of medium peak data rate, control plane latency of 20 ms and mobility covered up to 500 Km/h.

The key technical performance and requirements are set by 5G working group (5D) for the radio interfaces in its report[20] there should be peak data rate of 20 Gbps for DL and 10 Gbps for UL. The corresponding minimum spectral efficiencies are 30 bps/Hz and 15 bps/Hz respectively. Another key technical requirement is latency. The minimum user plane for a one-way data transmission is 4 ms for eMBB while 1 ms for URLLC will be required. As mentioned, the control plane latency between the idle state and data transfer can be as high as 20 ms. In case of mMTC, the density of connected devices with guaranteed Quality of Services (QoS) will be at least 1 million per km^2.

Current IMT systems are designed for sub 6 GHz bands where no more free spectrum bands are available. The 5G standardization works proceed developing the existing technologies as well as defining new RAN technologies termed as New Radio (NR), supporting a wide range of frequencies from <6 GHz all the way up to 60 GHz millimeter wave bands. The 3GPP's technical report[21] specifies the set of requirements and defines a range of deployment scenarios and associated requirements in terms of a carrier frequency, inter-site distance, user density and mobility.

To fulfil these broad set of requirements, new research directions will lead to fundamental changes and five disruptive technology that could lead to both architectural and component design change are [22]:

- **Device centric architectures**: base station centric architectures of cellular system change in 5G where conceptual rethinking of uplink and downlink as well as control and data channels will present device centric architecture.
- **Millimeter wave(mmWave):** while spectrum has become scarce at microwave frequencies, its plentiful in the mmWave realm.
- **Massive MIMO:** Multiple input and Multiple output will proposes utilizing a very high number of antennas to multiplex messages for several devices on each time-frequency resource, focusing the radiated energy toward the intended direction while minimizing intra and inter-cell interference.
- **Smarter devices:** 5G will have computing capabilities at device side shifting the previous practice of computation and control at the infrastructure side as in 2G, 3G and 4G. This lead to bringing device with intelligence, smart devices and allowing device-to-device (D2D) connectivity.
- **Native support for MTC:** 5G should support the use cases to a massive number of different class low data rate services and very low latency data transfer to the connected devices and applications.

2.2. Machine type communication

In the future, all devices that would benefit from an internet connection will be connected. In this Networked Society, every person and every industry will be empowered to reach their full potential. Internet of Things (IoT) technology is a key enabler of this vision by delivering machine-to-machine (M2M) and machine-to-person communication on a massive scale[23]. The trend and predictive analysis show that there will be billions of devices connected to the internet e.g., 26 billions connected devices by 2020[24] and 50 billions connections by 2025[25]. According to Cisco, the number of mobile-connected devices has exceed the number of people on earth[26]. While, the number of mobile subscription has reached 7.5 billion out of which 4.1 billion are broadband connections according to Ericsson[27]. By 2022, there will be 8.9 billion mobile subscriptions mostly from LTE and 5G.

These trends have also shown that the wireless cellular technologies are replacing fixed-line solutions. In future, in addition to Human-centric applications, wireless networks will see growing number of IoT applications such as smart grid, smart city, healthcare, automation and utility. Wireless Cellular networks are natural choice due to their already existing infrastructure, wide area coverage and high performance. Additionally, some MTC system already exist in cellular set up with low power wireless local area networks. MTC differs from HTC in different requirements concerned with uplink, downlink, subscriber load, device types, delay, energy, signalling and architectural requirements. Upcoming cellular technologies in the context of MTC over cellular can be summarized [28]. Some of the major requirements are:

- **Uplink:** for many MTC applications, the main bottleneck, high signalling overhead and extreme power constraints.
- **Downlink:** devices able to deep sleep, but wake up on command for network-initiated communication.
- **Subscriber load:** Many(»100) simultaneous device per cell with traffic uploading that can be even triggered, periodic or continuous.
- **Device types:** An extremely heterogeneous device landscape that includes environmental sensors, utility meters, wearable device and many unforeseen applications.
- **Delay requirements:** very divers delay requirements, ranging from emergency/time critical to very delay-tolerant applications.
- **Energy requirements:** many ultra-low energy applications that require extreme power consumption measures.
- **Signalling requirements:** application- dependent signalling protocols, with extremely efficient overhead signalling and contention resolution.
- **Architectural requirements:** wide area coverage may require integration of data aggregators with multihop relaying, relaxed requirements for handover and roaming support.

MTC has also opened the new horizontal market aspects for MNOs and MVNOs. In 3GPP Release 8 to Release 13 there has been mentioned MTC-specific features enhancements (core network, service architecture aspects and radio access network aspects). Some of the key technical requirements as standardization in 3GPP according to [29] are as follows:

- The need for MTC user identification.
- The need for coverage improvement.
- Service exposure and enablement support.

So mainly according to [29], 3GPP efforts have initially focused on identification of machine type devices to allow operators to selectively handled such devices in overload situations, subsequent effort on radio-level enhancements for complexity reduction, coverage improvement and reduction of UE power consumption and optimization for handling small data. Understanding the properties of MTC traffic is also considered as key for designing and optimizing future networks and the respective QoS schemes with the goal of provisioning adequate M2M services without compromising any conventional HTC services such as data, voice and video[30].

MTC can be categorized as mMTC which is concerned with wireless connectivity to tens of billions of machine type terminals and uMTC which is about availability, low latency, and high reliability. So for massive machine type communications (mMTC) in 5G some of the mentioned Physical and Access layer solution can be outlined as follows[31]:

- **Physical layer solutions:**
  1. Compressed -sensing based multi-user detection.
  2. Sparse code multiple access.
  3. Continuous Phase Modulation.
- **Access layer solutions:**
  1. Uplink SCMA contention-based Grant-Free transmission.
  2. Coded Random Access and CS-MUD.

The term uMTC refers to ultra-reliable low latency MTC and is discussed in detail later on section 2.3.

2.2.1. Wireless standard for massive MTC

Some current wireless standards support MTC applications. Some of the well-known technologies are a short-range solution such as Bluetooth Low Energy (BLE), Zigbee, WirelessHART, 6LoWPAN and Z-wave. In order to cover billions of connected IoT devices like sensors and actuators, these technologies require a gateway within a coverage range of tens or hundreds of meters.The gateway can also be connected to the internet through wired or wireless solutions. Some of mMTC solutions of LPWA technologies can encompass from both licensed and unlicensed bands. Some of the popular unlicensed bands technologies covering its application in the field like industrial, scientific and medical (ISM) band:

- LoRA
- SigFox
- Radio Phase Multiple Access (RPMA)

For the licensed band, 3GPP introduced the first IoT-specific UE category, known as LTE Cat-0 or LTE-M, in Release 12 [32]. Features of LTE-M are peak date rate of 1 Mb/s over 1.08 MHz BW and support for UEs with half duplex operation and power saving mode. Subsequently, 3GPP has standardized in Release 13, a new RAN technology called NB-IoT[33]. This new RAT is mostly concerned with indoor coverage specifying a 20 dB coverage enhancement compared to legacy GPRS systems. NB-IoT supports massive number of low throughput devices, low delay sensitivity and ultra low device cost and low power consumption (battery life up to 10 years). This technology can be essential for reducing deployment cost and time, because it can be upgraded in the current existing LTE network due to basic inbuilt properties and easily of combining with an upcoming 5G network. These wireless standard for MTC can be of great benefit to enable the MTC over a wireless cellular network and enhance the functionalities of MTC.

2.3. Ultra Reliable Low Latency Communication

URLLC consists of different scenarios and services that have different requirements. Some of the applications demand high reliability of up to $1-10^{-9}$ and a latency of 1 to 10 ms while other demands a reliability of $1-10^{-5}$ but with a very low latency of 1 ms. The later reliability and latency has been quiet popular in aspects of factory automation scenarios and 3GPP calls it as conventional industrial control applications[34].

Wireless technologies have attained full interest due to its flexibility and predicted lower cost. In this context, reliability refers to guaranteed message delivery within the required latency bound. It is typically quantified as the residual block error rate (BLER) at the physical layer (PHY) or the packet error rate (PER) at higher layers of the protocol stack. Latency is considered end-to-end (e2e) in factory automation, where one end is formed by sensing measured data and providing it to the process logic controller (PLC). While PLC comprises the essential logic to process the collected sensor data and instructs the actuators forming the other communication end[35]. However, both academia and industry are putting their successive effort to make this vision a reality in the near future.

2.3.1. Evaluation

Ultra reliable communication will be one of the novel features in the upcoming 5G system. Figure 2.2 illustrates the expected operating region of 5G wireless system in the context of data rate vs the number of users or connected devices in the service area. Contrary to a broadband regime, the region **R3** and most of **R4** features lowband data rates. In lowband communication the message sent from/to the devices are short. In the region **R3**, these short messages are coming from large number of machines and /sensors in e.g., the smart grid or environmental sensing. In the region **R4** the short messages are exchanged with very low latency. Region **R5** is impossible due to fundamental physical and information-theoretic limits[36].

It is obviously clear that MTC relies on the transmission of short packets as it is the typical generated traffic form by sensors and other measuring devices. Current wireless systems are not designed to support short packet transmission where these short packet carry critical information and should be received with very low latency and with high reliability. Additionally, when the packet is short, metadata may be of the same size as the payload, and conventions method to transmit it may be highly suboptimal[37].

The capacity of URLLC will be used as a performance metric for the evaluation and feature selection[38]. URLLC capacity describes how many UEs or how much load the network can support. URLLC capacity is different that of channel capacity and it is defined as [39],

Definition 1. *URLLC System capacity, $C(L,R,Y)$ is defined as the maximum off-cell load under which $Y\%$ of users in a cell operate with target link reliability R under latency bound L. $X = (100-Y)\%$ is the fraction of users in outage. A UE is in outage if UE can not meet the latency L and link reliability R requirements. URLLC is measured in bits per second[bits/s].*

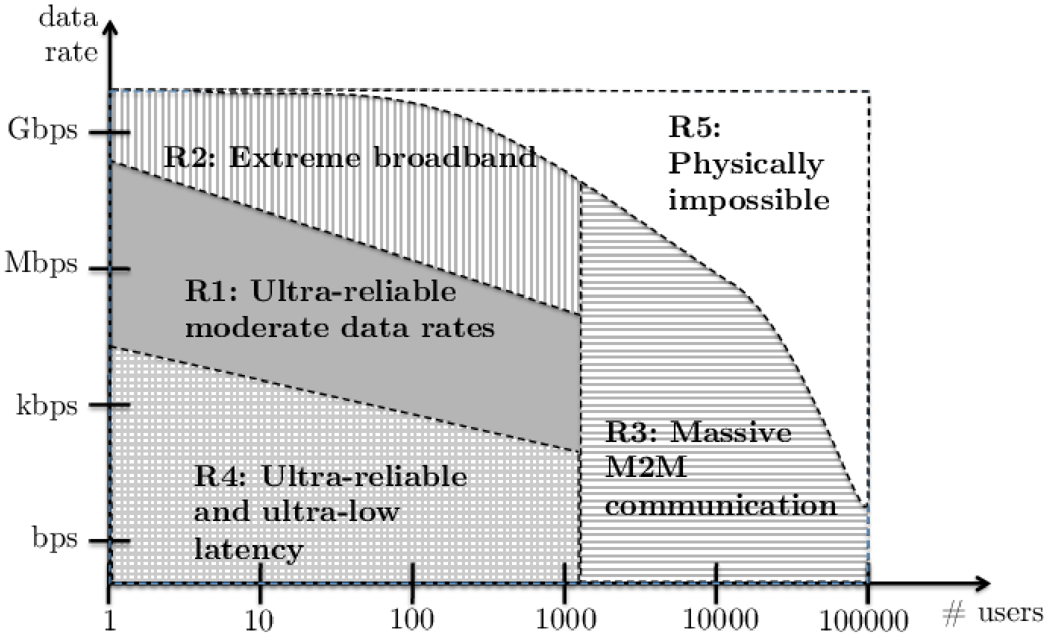

Figure 2.2: Operating region of the 5G wireless system[36].

In brief, when users increase, then the percentage of users meeting reliability and latency also get decreased. This definition gives the clear trade-off between latency, reliability, and scalability.

2.3.2. Requirements

The requirements of URLLC according to 3GPP is that reliability of transmission of 32 bytes should be $1 - 10^{-5}$, with a user plane latency of 1ms. User plane latency and reliability are defined in definition 2 and 3, according to current 3GPP agreements and as mentioned in [39] and [40].

Definition 2. ***(latency):*** *User plane latency (L) is defined as the time it takes to successfully deliver an application layer packet/message from the radio protocol layer entry point to the radio protocol layer exit point via the radio interface in both UL and DL directions, where neither device nor base station reception is restricted by Discontinuous Reception (DRX, a mode in which the UE sleeps for certain period)[40].*

Definition 3. ***(Reliability):*** *Reliability(R) is defined as the success probability of transmitting X bits within user plane latency (L) at a certain channel quality. The time of L seconds corresponds to the user plane latency and includes transmission latency, processing latency, retransmission latency and queuing/scheduling latency (including scheduling request and grant reception if any)[39].*

The way to generalize the latency and reliability is to plot the Cumulative distribution function (CDF) of the latency as shown in the Figure 2.3 where CDF shows that concerned latency will be less than or equal to a certain threshold. Due to transmission infrastructure failures all packets will not be received so there will be a probability of dropped packets. And as shown in figure with certain threshold reliability of successful transmission is measured and the given reliability corresponds to $1 - P_e$, where P_e is the transmission infrastructure failure or drop packets.

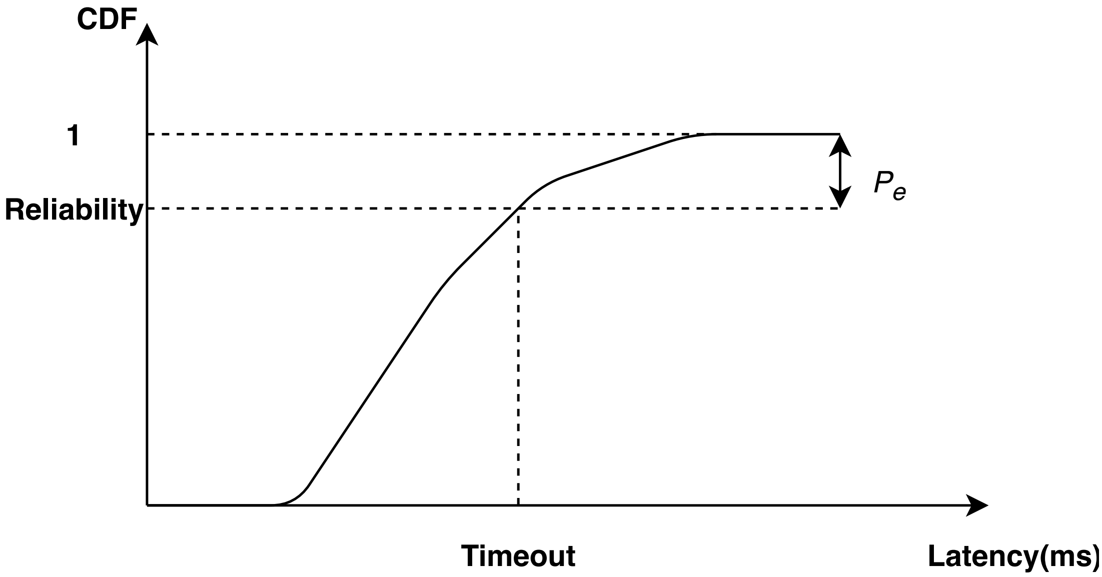

Figure 2.3: Conceptual illustration of latency-reliability function.

2.3.3. Building blocks and key enablers of URLLC

The demand for higher reliability and low latency in a use case of critical MTC in the 5G system is the way to look at system design and principles. The conceptual way to look at higher reliability is to expense of higher energy as the transmitted signal is proportional to the product of time duration and bandwidth of transmitted signal. The key building blocks and principles of URLLC is concerned not only with frequency diversity but also depends on other diverse sources such as access point diversity due to densification, spatial diversity due to massive number of antennas and interface diversity[41]. Interface diversity is a way to offer URLLC without intervention in the baseband/PHY layer and integrate multiple interfaces based on different technology[42].

Key enablers of URLLC is concerned with clearly looking at the way towards the concerned issues with low-latency and high-reliability. These enablers have a significant role to successfully deploy LLC, URC and URLLC services concerning how to trade-off between latency and reliability. Some of the key enablers for URLLC in case for low latency are short transmission interval (TTI), short frame structure, eMBB/URLLC multiplexing, edge computing and slicing, machine learning and AI on edge, grant-free vs grant based access, NOMA, LEO satellites and unmanned aerial vehicles/systems, joint flexible resource allocation for UL/DL. In the case for reliability some of the key enablers are multi-connectivity and harnessing time/frequency/RATs diversity, multicast and data duplications (content and computations), HARQ and short TTI, network slicing, manufacturing diversity via network coding and relaying, proactive packet drop and space-time block codes[43].

3. RELIABILITY AND DIVERSITY

The main target of the thesis is to analyse and implement diversity scheme to achieve URLLC requirements in certain MTC networks where reliability is the main constraint factor. There are different channel impairments such as noise, shadowing, path loss, fading. In wireless communication technologies, fading is one of most significant problem. Signal undergoes fading and to cope with the channel impairments, and in special to reach the URLLC target, diversity the ability to exploit channel variations in time, frequency and space for communication robustness is the most powerful tool in the physical layer for achieving high reliability in a fading channel. For wireless communications, a Rayleigh fading channel represents the most challenging case in terms of achieving high reliability due to deep fading[6].

There are different mechanisms to implement diversity scheme and some of them are spatial diversity which is the most common diversity scheme where numbers of antennas is used to copy the transmitted signal. Other, diversity schemes such as time diversity which is mostly applicable in digital transmission where same bit of information is transmitted repetitively at short time intervals and in frequency diversity where the transmission of signal is done by transmitting at two different frequency carriers achieving two independent versions of signal.

The system model used in this thesis explores spatial diversity and cooperation scheme to which we propose analytical closed-form solution develop strategies that could achieve target URLLC requirements. In system model, there is one typical link and other interfering RRHs which can or can't cooperate with typical link for sending message or packets. We here use spatial diversity and cooperation among base station to reach out URLLC requirements when user equipment uses different schemes like cooperation ($k - out - N$), SC and MRC. The cooperation is facilitated through the use of concepts edge computing which can bring computational capabilities at edge of networks. Dense deployment of the future network, cooperatively executing computation task with multiple edge nodes (ENs) is promising to further shorten the latency[44].

In this chapter, network scenario and system model are described which gives the clear outlook to implement diversity schemes for enhanced reliability and to do so we use concepts of edge computing so to meet stringent latency.

3.1. Scenario

The scenario is developed considering the future networks which would satisfy the different verticals of 5G communication. Different emerging technologies will rise critical services within a 5G networks posing new challenges and the solution proposed herein to network design are a way to overcome some of those challenges. Such technologies are control robotics, factory automation, augmented reality, intelligent transportation, healthcare, gaming[45].

For URLLC based scenarios, as mentioned in [44][46][47] latency and reliability cannot be considered separately. However, it is challenging to achieve minimal latency and maximal reliability simultaneously. For the purpose to assure reliability requires high quality of connections and the purposed network scenario has subtask offloading through the different enhanced node (ENs), as given in Figure 3.1, where ENs or access points have capabilities of edge computing where the data processing can be done at the edge of network which reduced the downside of cloud computing by shortening the transmission time interval and lowering down the latency between central cloud computing unit and network. As mentioned in [48] edge-fog cloud offers several benefits likewise reduced network load, native support for mobility, providing context, no single point of failure. Applications such as connected vehicles, energy monitoring, automated traffic control can highly benefit from such architectures as most of the tasks in these type of applications are distributed and network-constrained.

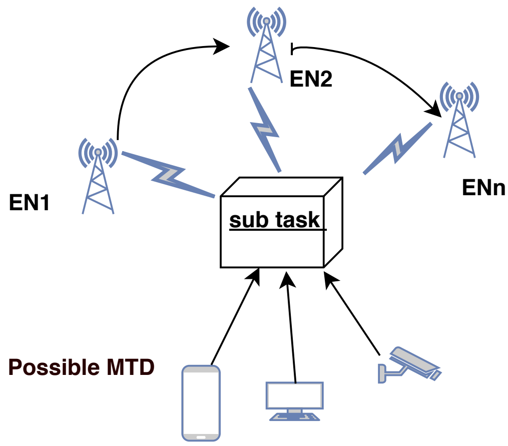

Figure 3.1: Overview of a possible network scenario.

3.2. System model

In the proposed work, a system model consists of single user equipment, UE i.e any MTC device or actuator with single antenna and N Remote Radio Heads (RRHs) denoted by η, equipped with computation and storage units which enable edge computing scenario which in further connected with cloud links as shown in Figure 3.2. In the topology, there is a typical link which is assumed to be in close with user equipment and other distributed RRH's which are in equidistant with user equipment. The links are further connected to cloud networks where baseband unit (BBU) is present by wireless or fixed line connections.

Consider a multi-node downlink cellular network in which there are $\eta + 1$ RRHs spatially distributed in a given area $\mathcal{A} \subseteq \mathbb{R}^2$. We assume constant rate transmission so that all other $\mathrm{RRH}_j,\ j = 1 \ldots \eta$ are using the same channel to transmit data to their corresponding user equipment UE, UE_j. Here, we denoted the distance between UE and RRH_0 as the distance between typical link and UE by d_0 and distance between $\mathrm{RRH}_j,\ j = 1 \ldots \eta$, as distance between UE and interfering link by $d_j, j = 1 \ldots \eta$. We assume channel undergoes Rayleigh fading and path loss exponent is denoted by α.

We focus on the analysis of the typical link's performance when the remaining RRHs are:

- not cooperating(thus, not edge computing or C-RAN enabled).
- Cooperating through the C-RAN.

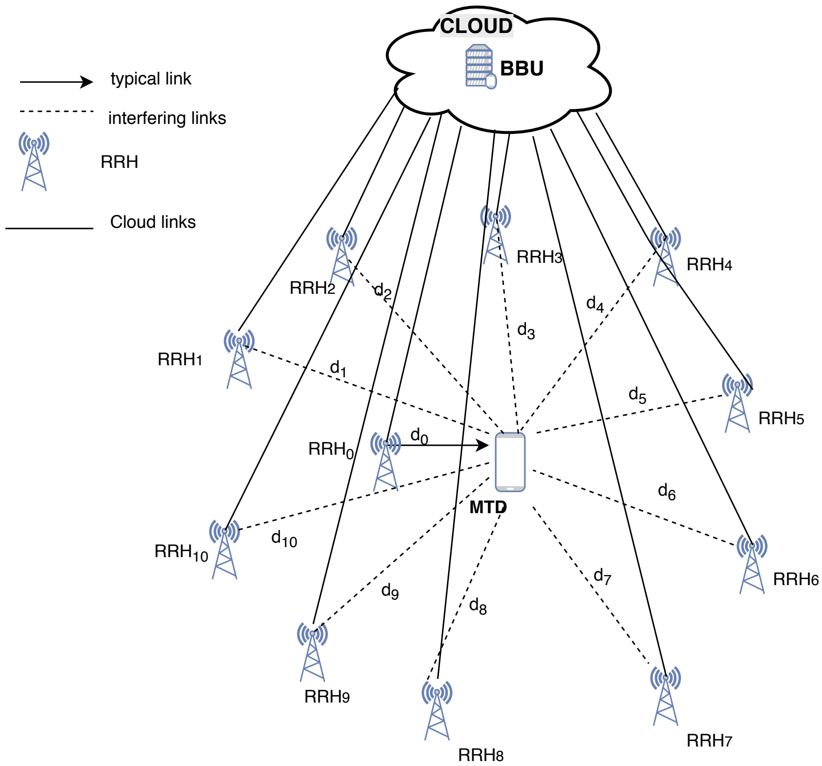

Figure 3.2: Illustration of system model with $\eta = 10$ RRHs.

Furthermore, MTD is equipped with single antennas. Assume that the received signal is independent and each fading can be treated as independent events and gains from spatial diversity can be attained. The system model is schematically illustrated in Figure 3.2.

Consider that each RRH transmit with fixed unit power as well as dense deployment such that network is interference limited, therefore the impact of noise can be neglected.

Under this settings, Signal-to-Interference Ratio at UE is given by,

$$SIR = \frac{\sum_{i=0}^{k} h_i d_i^{-\alpha}}{I_j} \tag{1}$$

Where, k is the number of RRHs cooperation's and I_j is the interference from the other remaining RRHs. We assume that $h_i \sim \text{Exp}(1)$ are the squared-envelop coefficients of the typical link and cooperating RRHs. While h_j is the squared-envelop of the channel coefficients of the interfering links, while their distances is denoted by d_i and d_j, respectively. Note that d_0 is the distance of the reference or typical link.

Under these assumptions, we calculate outage probabilities for the different scenarios and derive the closed-form solutions that would be helpful to achieve target outage probabilities. For the proposed scenarios we provide Cummulative Distribution Functions (CDF) and corresponding probability density functions (PDF). The analytical results are corroborated via Monte Carlo simulations.

3.3. Analysis with full interference scenario

Herein, we consider the typical link experiences interference from neighbouring RRHs, due to lack of coordination or lack of backhaul infrastructure for enabling the C-RAN (edge computing capabilities). The outage occurs when over $SIR < \theta, \theta = 2^r - 1$, where θ and r are the threshold and targeted transmission rate respectively. Thus, to calculate the necessary SIR, as the channel coefficient are Random Variables (RV's) we need to attain the distribution of SIR as,

$$F_{SIR} = \mathbb{P}(SIR < \theta) \tag{2}$$

Where F_{SIR} denotes the CDF of the SIR.
From (2) and for full interference scenario the CDF of the SIR is,

$$F_{SIR} = \mathbb{P}\left(\frac{h_0 d_0^{-\alpha}}{\sum\limits_{j=1}^{\eta} h_j d_j^{-\alpha}} < \theta\right) \tag{3}$$

$$F_{SIR} = \mathbb{P}\left(h_0 < \theta\Big(\frac{d_0}{d_j}\Big)^{\alpha} \sum_{j=1}^{\eta} h_j\right) \tag{4}$$

The difference with the calculation as with proposed system model in this thesis is that the interfering RRHs are in equidistant with the user equipment and the distance d_j can be treated as constant scalar quantity and the closed form solution can be derived as[14].

Where, $h_0 \sim \mathrm{Exp}(1)$ is a normalized exponential distributed RV with Cummulative distributed function (CDF) given as,

$$F_{SIR}(\theta) = 1 - \exp\big(-\theta\big(\frac{d_0}{d_j}\big)^{\alpha} \sum_{j=1}^{\eta} h_j\big) \tag{5}$$

Here,$h_j \sim \mathrm{Exp}(1)$ is also a normalized RV and $\sum\limits_{j=1}^{\eta} h_j$ is the sum of exponentially distributed random variable follows gamma distribution[49]. Let, $\mathrm{q} = \sum\limits_{j=1}^{\eta} h_j$ is also a RV whose PDF is given as,

$$\mathrm{f_q} = \frac{\mathrm{q}^{\eta-1}\mathrm{e}^{-\mathrm{q}}}{(\eta-1)!} \tag{6}$$

(4) is conditioned on h_0 and h_j where η is the total RRHs and next we proceed to calculate the CDF as,

$$F_{SIR}(\theta) = \int_0^{\infty} (1 - \exp(-\theta\big(\frac{d_0}{d_j}\big)^{\alpha}\mathrm{q})\mathrm{f_q}\mathrm{dq} \tag{7}$$

With simplification (7) can be reduced to

$$F_{SIR}(\theta) = 1 - \int_{0}^{\infty} (\exp(-\theta(\frac{d_0}{d_j})^{\alpha}\mathrm{q})\Big(\frac{\mathrm{q}^{\eta-1}\mathrm{e}^{-\mathrm{q}}}{(\eta-1)!}\Big)\mathrm{dq}$$

$$\overset{(a)}{=} 1 - \int_{0}^{\infty} \Big(\exp(-\mathrm{q}(1+(\frac{d_0}{d_j})^{\alpha}\theta)\Big)\frac{\mathrm{q}^{\eta-1}}{(\eta-1)!}\mathrm{dq} \tag{8}$$

In (8), we substitute the exponent of the exponential in (a) with x follows for integral limit thus $\mathrm{p} \to \infty$ then $x \to \infty$ and in the same way when $\mathrm{p} \to 0$ then $x \to 0$ where $\mathrm{dq} = \frac{dx}{\left(1+\left(\frac{d_0}{d_j}\right)^{\alpha}\theta\right)}$ and the following equation can be reduced to form as,

$$F_{SIR}(\theta) = 1 - \frac{1}{(\eta-1)!(1+(\frac{d_0}{d_j})^{\alpha}\theta)^{\eta}} \int_{0}^{\infty} \mathrm{e}^{-x}x^{\eta-1}dx \tag{9}$$

Here, the integral is lower incomplete gamma function[49] and the expression can be reduced to the following form as,

$$F_{SIR}(\theta) = 1 - \frac{1}{(\eta-1)!\Big(1+(\frac{d_0}{d_j})^{\alpha}\theta\Big)^{\eta}}\Gamma(\eta) \tag{10}$$

$$\overset{(a)}{=} 1 - \Big(1+(\frac{d_0}{d_j})^{\alpha}\theta\Big)^{-\eta} \tag{11}$$

Note that (a), in (11) is our final analytical closed-form solution for the full interference scenario.

3.4. Analysis with cooperation scenario:interference reduction

In this section we are silencing some RRHs and analysing the outage probability with $k-out-N$ strategies where k interfering RRHs are involved in the action and rest are in silent mode. The closed form solution can be derived by taking in account that interference reduces to $I_j = \sum_{j=k+1}^{\eta} h_j d_j^{-\alpha}$. Therefore, analytical expression can be attained as in section (3.3) as follows:

$$F_{SIR}(\theta) = 1 - \Big(1+(\frac{d_0}{d_j})^{\alpha}\theta\Big)^{-(\eta-k)} \tag{12}$$

If $k=0$, then the case will be subjected to full interference scenario else the desired solution will result in cooperation scheme.

In Figure 3.3, it is clearly shown that multiple RRHs in cooperation can significantly improve the outage probabilities as multiple connections leads to increase SIR and significantly improving outage probabilities.

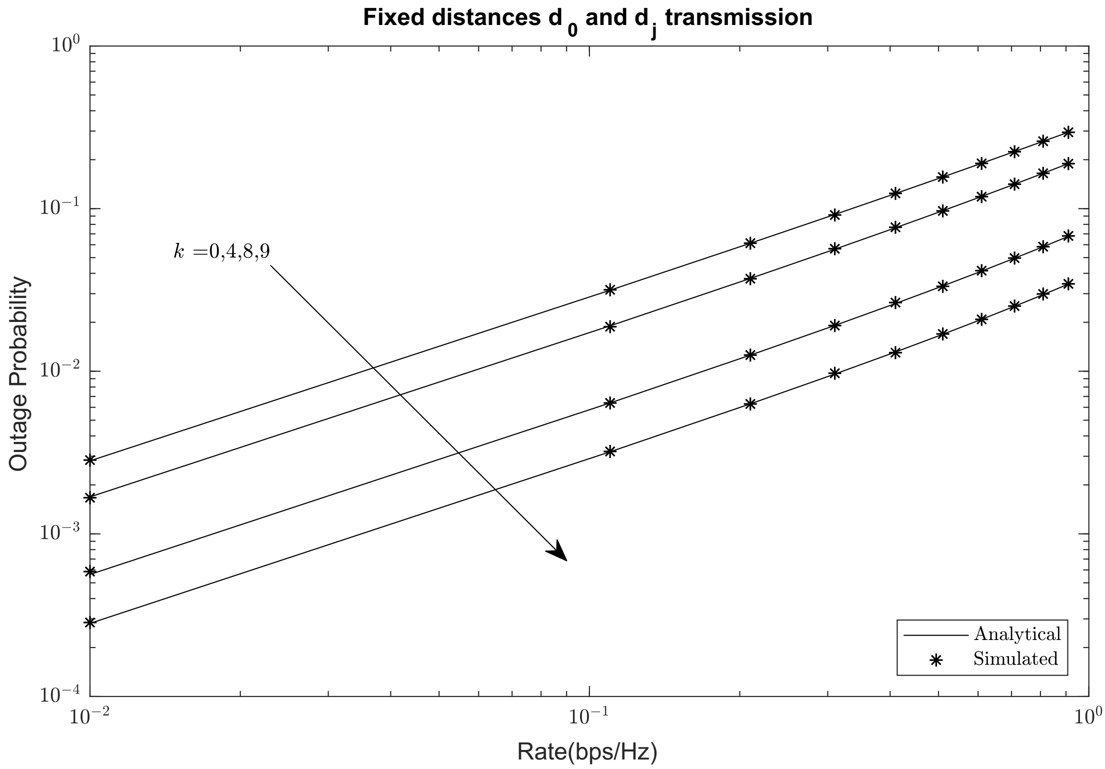

Figure 3.3: Illustration of cooperation scheme with $\eta = 10$.

3.5. Cooperation and diversity schemes

In the proposed analysis, we use cooperation analysis of interfering RRHs that are in action in sending the message along with reference RRH where rest of RRH are interfering. This scheme when RRH are in cooperation helps in enhancing reliability as interference is limited. The diversity schemes like Selection Combining (SC) and Maximum Ratio Combining (MRC) are used by UE to enhance gain. The corresponding analysis of diversity schemes are given below with their corresponding analytical solution:

3.5.1. Analysis with Selection Combining scenario

In this scenario, UE uses selection combining strategy in receiving the signal from transmitter. Assuming that the distance to UE from typical and interfering RRHs are fixed. In selection combining strategies UE selects the maximum SIR received so as the gain from this scheme could improve the target outage probabilities. Here, along with SC we proposed $k-out-N$ RRHs along in cooperation to reduce the interference from interfering RRH so that to improve outage probabilities and possibly maintain the targeted reliability constraint.

Thus, the outage probability is,

$$F_{SIR}(\theta) = \mathbb{P}\left(\frac{\Omega}{\sum\limits_{j=k+1}^{\eta} h_j} < \theta\right) \tag{13}$$

Where,

$$\Omega = \mathbb{P}(\max(h_0 d_0^{-\alpha}, \max(h_1......h_k) d_j^{-\alpha} < \theta) \tag{14}$$

Note that in (14), $j = 1 \ldots k$ is the number of RRHs in cooperation and we take the maximum between typical and interfering RRHs in cooperation. Now from (13) and (14) problem can be formulated as,

$$F_{SIR}(\theta) = \mathbb{P}\left(\frac{\max(h_0......h_k) d_j^{-\alpha}}{\mathrm{Z}} < \theta\right) \tag{15}$$

Let, $\mathrm{Z} = \sum\limits_{j=k+1}^{\eta} h_j$ be a gamma distributed RV such that $\mathrm{Z} \sim \mathrm{Gamma}(\mathrm{k}, \eta)$ distribution then (15) can be written conditioned on Z as,

$$F_{SIR}(\theta) = \mathbb{P}\left(h_0 d_0^{-\alpha}, max(h_1......h_k) d_j^{-\alpha} < \theta Z\right) \tag{16}$$

From (16) we attain,

$$F_{SIR}(\theta) = (1 - \exp(-\theta \mathrm{Z} d_0^{\alpha} d_j^{-\alpha})(1 - \mathrm{e}^{-\theta \mathrm{Z}})^k \tag{17}$$

which comes straight from higher order statistics[50].
Then, de-conditioning (17) we have

$$F_{SIR}(\theta) = \int_0^{\infty} (1 - \exp(-\theta \mathrm{Z} d_0^{\alpha} d_j^{-\alpha}))\, \underbrace{(1 - \mathrm{e}^{-\theta \mathrm{Z}})^k}_{(a)}\, \mathrm{f_Z dz} \tag{18}$$

By using binomial theorem $(1 + x)^n = \sum\limits_{k=0}^{n} \binom{n}{k} x^k$ to expand term (a) in (18) we obtain

$$(1 - \mathrm{e}^{-\theta \mathrm{Z}})^k = \sum_{t=0}^{k} \binom{k}{t} (-1)^t (-\mathrm{e}^{-\theta \mathrm{Z}})^t \tag{19}$$

Then after substitution (18) is rewritten as,

$$F_{SIR}(\theta) = \sum_{t=0}^{k} \binom{k}{t} \int_{0}^{\infty} \left(1 - \exp(-\theta \mathrm{Z} d_0^{\alpha} d_j^{-\alpha})\right)(-1)^t (\mathrm{e}^{-\theta \mathrm{Z}})^t \left(\frac{\mathrm{Z}^{\eta-k-1} \mathrm{e}^{-\mathrm{Z}}}{(\eta-k-1)!} \right) \mathrm{dz} \tag{20}$$

Simplifying (20),

$$F_{SIR}(\theta) = \sum_{t=0}^{k} \binom{k}{t} \frac{(-1)^t}{(\eta-k-1)!} \int_{0}^{\infty} \Big(\mathrm{Z}^{\eta-k-1} \exp(-\mathrm{Z}(1+\theta t)) - \mathrm{Z}^{\eta-k-1} \exp(-\mathrm{Z}(1+\theta t + \theta d_0^{\alpha} d_j^{-\alpha})) \Big) \mathrm{dZ} \tag{21}$$

Let, $\mathrm{Z}(1+\theta t) = x$ and $\mathrm{Z}(1+\theta t + \theta d_0^{\alpha} d_j^{-\alpha}) = y$ then when $\mathrm{Z} \to 0$ then $x, y \to 0$ and when $\mathrm{Z} \to \infty$ then $x, y \to \infty$ and with the substitution $\mathrm{dz} = \frac{dx}{(1+\theta t)}$ and for $y, \mathrm{dz} = \frac{dy}{(1+\theta t + \theta d_0^{\alpha} d_j^{-\alpha})}$ and with these variables (21) can be reduced to form as,

$$F_{SIR}(\theta) = \sum_{t=0}^{k} \binom{k}{t} \frac{1}{(\eta-k-1)!} (-1)^t \left(\left((1+\theta t)^{k-\eta} \int_{0}^{\infty} \mathrm{e}^{-x} x^{\eta-k-1} dx \right) - \left((1+\theta t + \theta d_0^{\alpha} d_j^{-\alpha})^{k-\eta} \int_{0}^{\infty} \mathrm{e}^{-y} y^{\eta-k-1} dy \right) \right) \tag{22}$$

In (22) the integrals are gamma function as, $\Gamma(s) = \int_{0}^{\infty} t^{s-1} \mathrm{e}^{-t} dt$, where $s > 0$ simplifying (22) yields,

$$F_{SIR}(\theta) = \sum_{t=0}^{k} \binom{k}{t} \frac{1}{(n-k-1)} (-1)^t \left(\left((1+\theta t)^{k-\eta} \Gamma(\eta-k) \right) - \left((1+\theta t + \theta d_0^{\alpha} d_j^{-\alpha})^{k-\eta} \Gamma(\eta-k) \right) \right) \tag{23}$$

$$F_{SIR}(\theta) = \sum_{t=0}^{k} \binom{k}{t} (-1)^t \left((1+\theta t)^{k-\eta} - \left(1 + \theta t + \theta d_0^{\alpha} d_j^{-\alpha} \right)^{k-\eta} \right) \tag{24}$$

If $k = 0$, case is full interference single connectivity of typical link else, $k > 0$ is cooperation with multiple RRHs in transmission with selection combining strategy.

Figure 3.4 illustrates $k = 0$ is a case of full interference and as k increases the cooperation of RRHS increases and multi connectivity to the UE with multiple RRHs significantly improved the outage probabilities and maintain the reliability across rate. It is clearly shown that monte carlo simulations in Figure 3.4 matches the analytical analysis derived in (24).

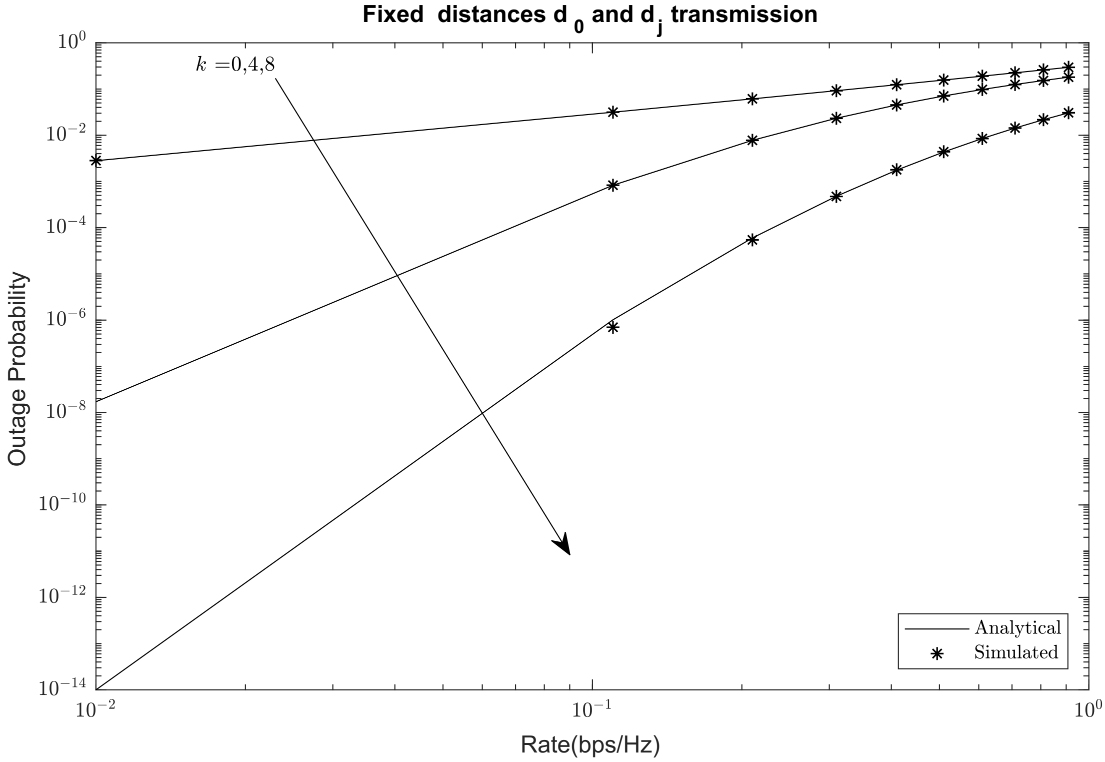

Figure 3.4: Comparing analytical and simulated result for SC for different rate with $\eta = 10$, for different number of cooperating RRHs.

3.5.2. Analysis with Maximum Ratio Combining scenario

Maximum ratio combining is the scheme where UE performs linear combining of the SIR from typical as well as from the interfering base station which are jointly involved in cooperation of transmission. The CDF in the case when UE uses the MRC scheme can be defined as,

$$F_{SIR}(\theta) = \mathbb{P}\left(\frac{h_0 d_0^{-\alpha} + \sum\limits_{i=1}^{k} h_i d^{-\alpha}}{\sum\limits_{j=k+1}^{\eta} h_j d^{-\alpha}} < \theta \right) \tag{25}$$

In (25), $h_0, h_i, h_j \sim \mathrm{Exp}(1)$ and is a exponentially distributed RV and $d = d_j$. Note that the numerator and denominator are composed of sums of exponentially distributed RVs, therefore RV, $\mathrm{P} = \sum\limits_{i=1}^{k} h_i$ and $\mathrm{q} = \sum\limits_{j=k+1}^{\eta} h_j$ then (25) can be reduced to,

$$F_{SIR}(\theta) = \mathbb{P}\left(\frac{h_0 d_0^{-\alpha} + \mathrm{P} d_j^{-\alpha}}{\mathrm{q} d_j^{-\alpha}} < \theta \right) = \mathbb{P}\left(h_0 < \left(\frac{d_0}{d_j}\right)^{\alpha} (\theta \mathrm{q} - \mathrm{P}) \right) \tag{26}$$

Then, after adjusting the limits in (26) we attain

$$F_{SIR}(\theta) = \int_{\frac{\mathrm{P}}{2^r-1}}^{\infty} \int_{0}^{\infty} (1 - \exp((-(\frac{d_0}{d_j})^\alpha(\theta\mathrm{P} - \mathrm{q})))\mathrm{fpfqdpdq} \quad (27)$$

Note that in (27)the inner integral with respect to P is the lower incomplete gamma function can be solved as the procedure in subsection 3.5.1, but as the outer integral needs a more careful analysis and for $\left(\frac{d_0}{d_j}\right)^\alpha < 1$ it can be solved as,

$$\begin{aligned} F_{SIR}(\theta) = \frac{1}{\Gamma(\eta - k)}\theta^k\Big(1 + (\frac{d_o}{d_j})^\alpha\theta\Big)^{-\eta}\Gamma(\eta) \\ \Bigg(\Big(1 + (\frac{d_0}{d_j})^\alpha\theta\Big)^{\eta} {}_2F_1(k, \eta, 1 + k, -\theta) \\ - {}_2F_1(k, \eta, 1 + k, \frac{\Big(-1 + (\frac{d_0}{d_j})^\alpha\theta\Big)}{\Big(1 + (\frac{d_0}{d_j})^\alpha\theta\Big)}\Bigg) \end{aligned} \quad (28)$$

Note (28) is our final closed-form solution with the hypergeometric regularized function [51] expression to make the analysis with MRC scheme for the given scenario. Note that (28) was attained with help of Mathematica[52].

Figure 3.5 illustrates that analytical and simulated result perfectly matches it and whenever neighbouring interfering RRHs are in cooperation and UE use MRC scheme

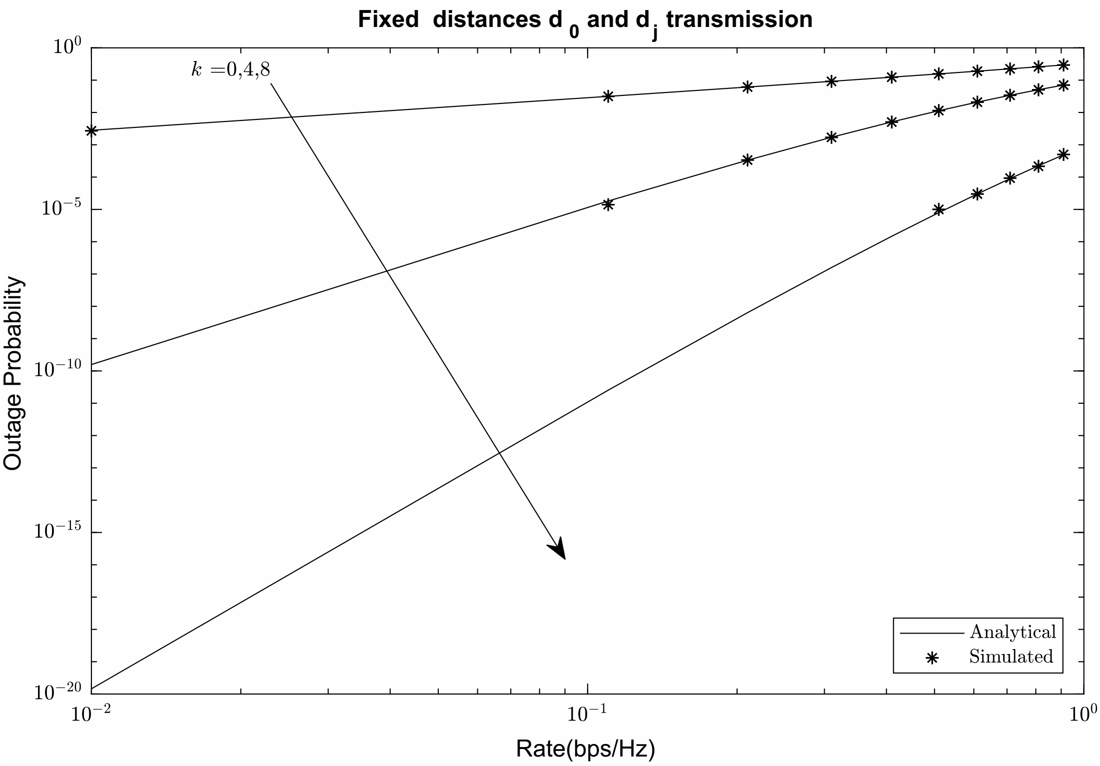

Figure 3.5: Comparing analytical and simulated result for MRC for different rate with $\eta = 10$.

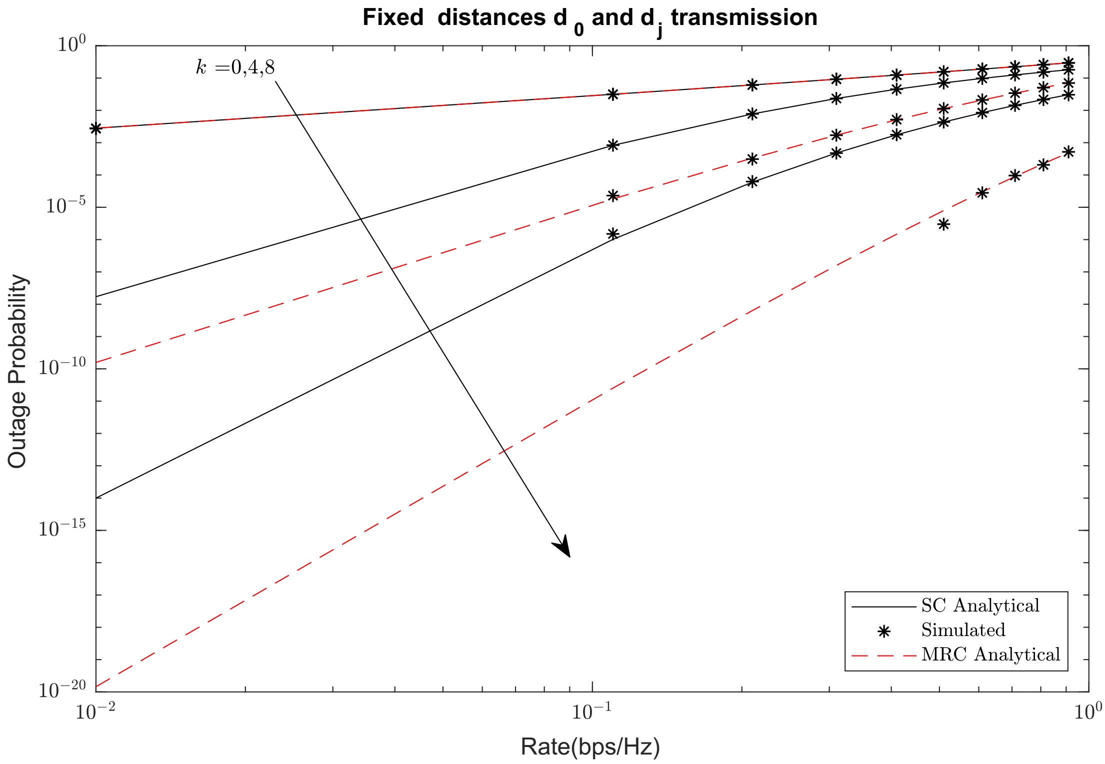

Figure 3.6: Comparative illustration of analytical and simulated result for SC and MRC for different rate with $\eta = 10$.

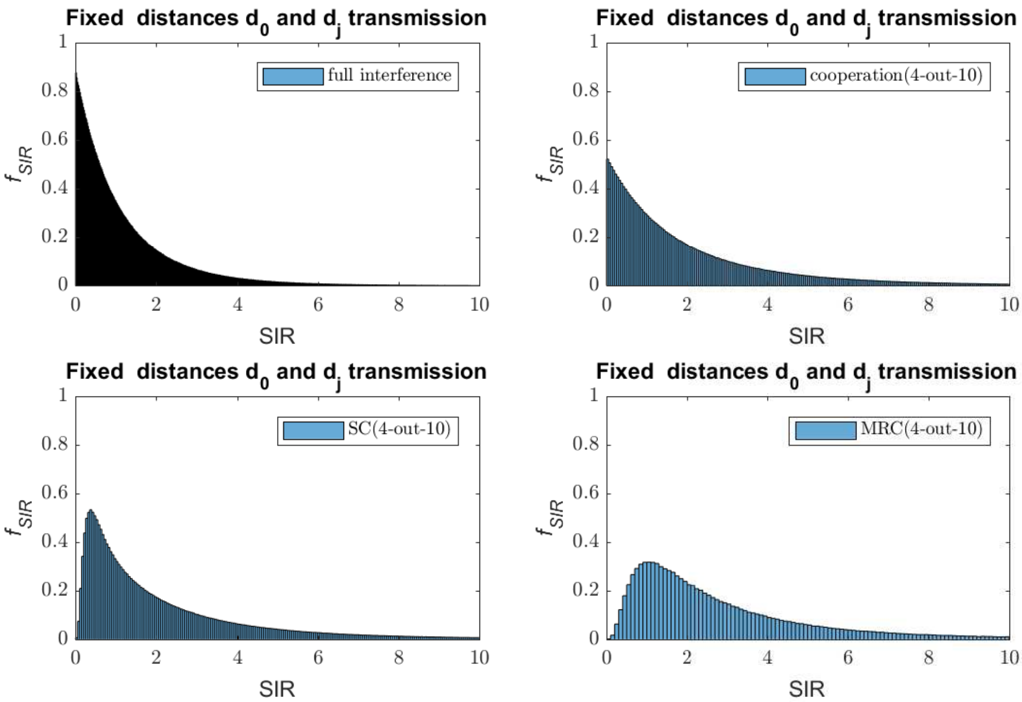

Figure 3.7: Overview of SIR distribution for full interference,$(k\!-\!out\!-\!N)$cooperation, SC and MRC schemes.

gain can be significantly improved from the outage probabilities and reliability can be maintained in critical MTC services.

From Figure 3.6, it can be observed that the gain from outage probabilities from MRC outperform SC, while both outperforms full interference scenario. The comparative analysis shows multi-connectivity scenario improves spatial diversity scheme to combat with fading impairments and thereby to gain more reliability in connection for demanding user services or types of equipment. However, such schemes require complex design at receiver side which can be expensive in implementation.

Figure 3.7 shows the SIR distribution for different schemes full interference, $k - out - N$ cooperation, SC, MRC with fixed distance $d_0 = 20m$ and $d_j = 40m$ respectively as well as with $\eta = 10$ and $k = 4$. From distribution it is clear that probability of calculating SIR is between 0 and 2. In case of full interference and $(k - out - N)$ schemes nature of distribution is same but the performance is more better due to less interference in cooperating RRHs schemes although there is no gain from diversity. But, in case of cooperation and diversity schemes for SC and MRC, the graph shift more to right tail and the gain through diversity can be observed and MRC schemes shows superior performance than compared to SC and other schemes.

4. NUMERICAL RESULTS AND DISCUSSION

In Chapter 3, the analysis of system model with the different scheme are presented and in this chapter, we provide numerical analysis and discussion.

4.1. Method

Herein, we evaluate a multi-connectivity scenario in downlink and develop a transmission strategy that would best fit to achieve targeted outage probabilities of 10^{-5}. The problem was to analyse the model and derive closed-form analysis of different schemes and to design, implement, simulate and evaluate the proposed methods. In the analysis we have used Monte Carlo simulation of 10^7 runs, some schemes not closely match the targeted reliability of 10^{-5} as it requires longer simulation samples. Further work is required so to improve the accuracy on the tail of the distribution.

Numerical results are presented in terms of different analysis under threshold, θ, which represents the target SNR, typical link distance, d_0 and interfering link distance, d_j defining the outage probabilities for the topology consisting of $\eta = 10$ RRHs and corresponding k, which are cooperating RRHs for transmission to limit the interference factor. Results presented hereafter are for the path loss exponent $\alpha = 3.5$, unless stated otherwise.

4.2. Analysis of the $F(\theta)$-CDF of SIR

Herein, we evaluate the CDF of SIR, where θ denotes SIR threshold for the different proposed scenarios. In the analysis typical and cooperating RRHs distances are fixed and analysis is done by varying threshold with a number of RRHs, $\eta = 10$.

4.2.1. Full interference and $k - out - N$ cooperation

In this section, we consider full interference and $k - out - N$ cooperation scenarios to evaluate the system performance according to (11) and (12) as detailed in Chapter 3.

From Figure 4.1, it can be shown that outage increases whenever the value of threshold increases. In the case $k = 0$, full interference case where all the interfering RRHs are interfering the performance is same for all the schemes no gain from diversity. Whenever the number of cooperating RRHs, increases e.g., $k = 4, 8, 9$ means that neighbourhood RRHs are coordinated as to cooperate and reduce interference, thus outage can be significantly improved. This scenario shows that more RRHs in cooperation, and thereby limiting interference, improves reliability. However, it requires coordination and smart scheduling solutions to relocate the traffic of cooperating RRHs, being thus an efficient solution when η is small and network is less busy.

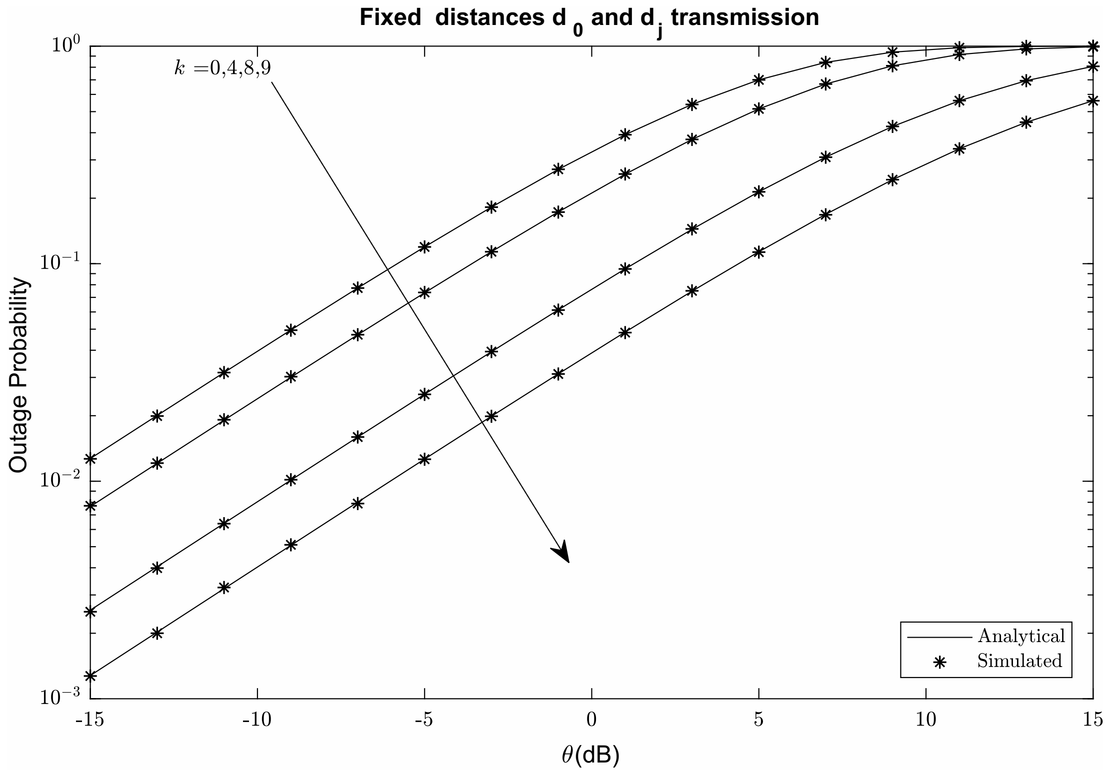

Figure 4.1: Illustration of cooperation strategy with a threshold θ and $\eta = 10$.

4.2.2. Selection Combining

In the proposed analysis UE performs SC where maximum of recieved signal is taken and we consider received SIR as in (24) obtained in Chapter 3.

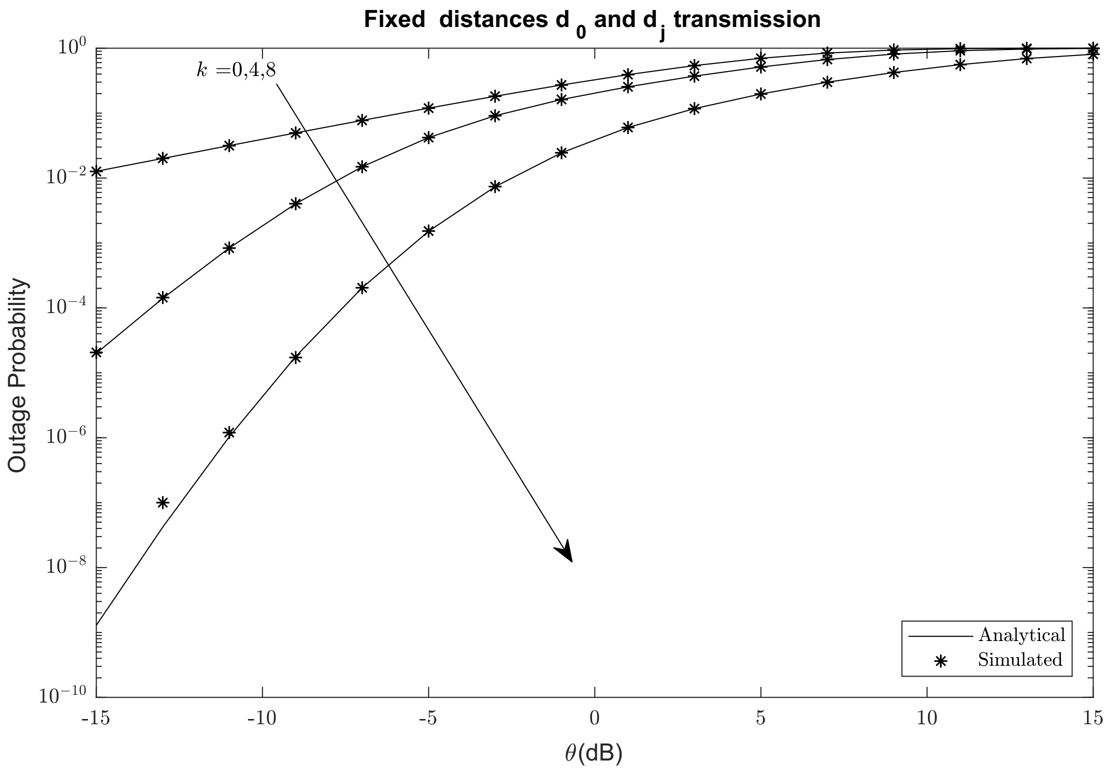

Figure 4.2: Illustration of selection combining strategy with a threshold θ and $\eta = 10$.

From Figure 4.2, in the case, $k = 0$ for full interference case the outage probabilities has no any significant improvement but whenever neighbouring RRHs are in cooperation for transmission then reliability has significant improvement. It is clear that cooperation of RRHS along with selection combining diversity scheme can limit the interference and significantly improve the outage probabilities even for the high threshold. Note that $k = 4$, 4 RRHs out of η, cooperation can reach the target outage probabilities, for instance clearly larger gains can be achieved for larger k.

4.2.3. Maximum Ratio Combining

In the proposed analysis, UE performs MRC where the received signal are combined along with a typical link to get higher SIR and outage can be improved. In this analysis we are considering (28) for analytical analysis as detailed in Section 3.5.2.

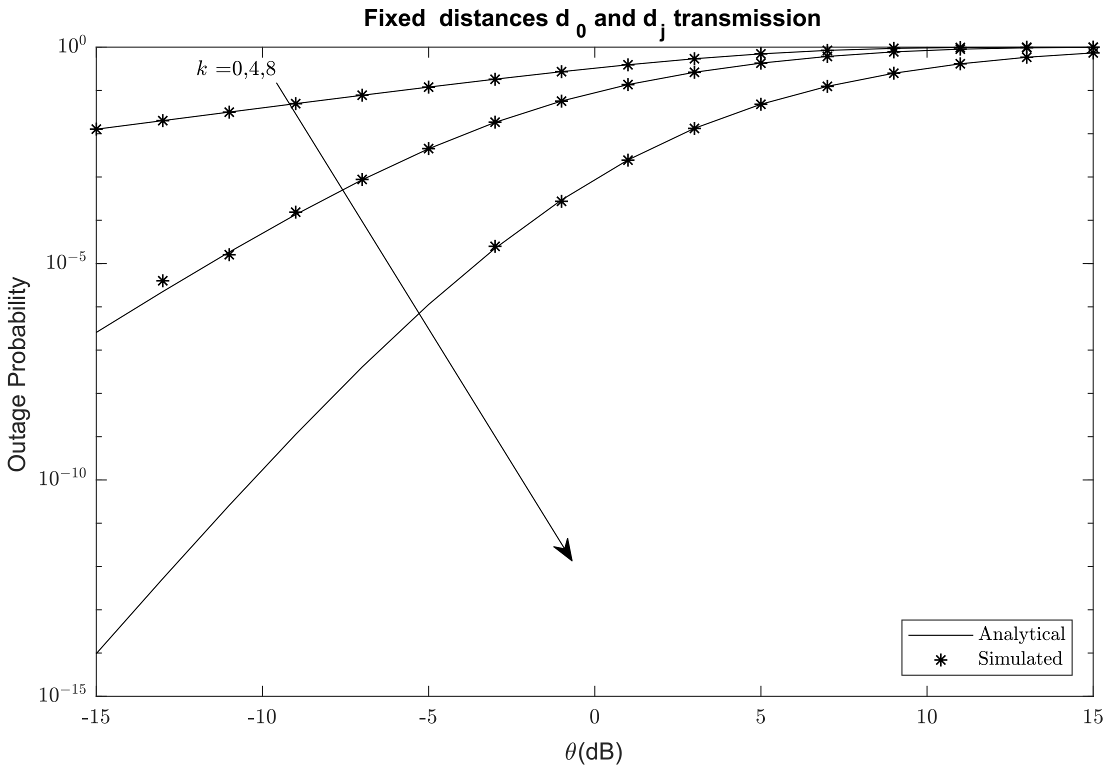

Figure 4.3: Illustration of maximum ratio combining strategy with a threshold θ and $\eta = 10$.

Figure 4.3, shows that with $k = 0$, full interference from RRH in a given area has not any significant change in the outage probabilities but as k get increased i.e cooperation of RRHs limiting the interference from the neighbouring RRHs can have huge impact on outage probabilities. For instance $k = 4$ can be reached the targeted outage probabilities with low threshold. However, so to achieve low outage probabilities in higher threshold value, more RRHs in cooperation is needed to be increased to have higher degrees of freedom.

From figure 4.4, it is clear that among both the scheme in comparison MRC outperform SC in system performance for the same distances on analysis and same number of base station with respect to given threshold. The shaded region in graph represent

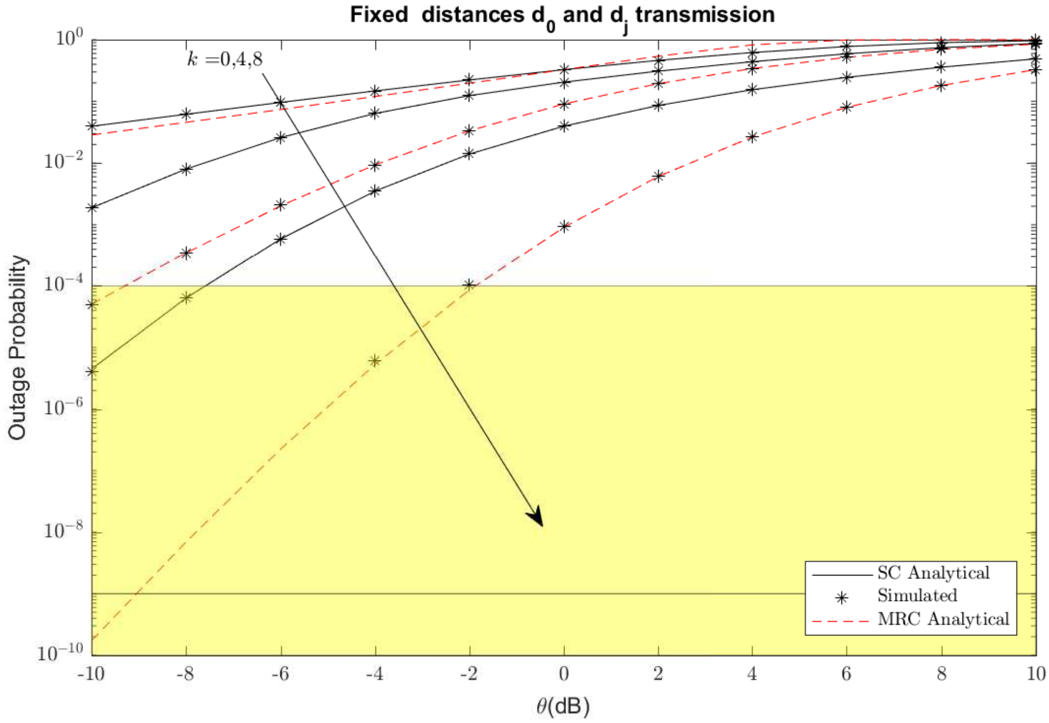

Figure 4.4: Comparative illustration of SC and MRC with a threshold θ and $\eta = 10$.

ultra reliable operation region as mentioned by some standardization bodies. The performance evaluation shows that MRC has more penetration towards feasibility of ultra reliable region operation for e.g., even with $k = 4$ RRHs in cooperation can reach the target reliability and can go along higher threshold value while SC schmes with more RRHs in cooperation can only penetrate the ultra reliable region. Thus, the diversity gain from MRC is higher than SC for a given threshold and same number of cooperating RRHs.

4.3. Results with Typical link distance analysis

In this section, system performance is evaluated varying typical RRH link distance to UE. For proposed analysis, we fixed transmission rate (1bps/Hz) as well as cooperating RRHs interfering link distance (i.e 50 meter) and system performance is measured when UE performs different diversity schemes.

4.3.1. Full interference and $(k - out - N)$ *cooperation*

Figure 4.5, shows that whenever the typical link is in close with the UE outage probability is low. Here in the scenario when cooperation of RRHs k is increased for e.g., $k = 0, 4, 8, 9$ then for same typical link distance lower outage can be achieved as cooperation can limit the interference.

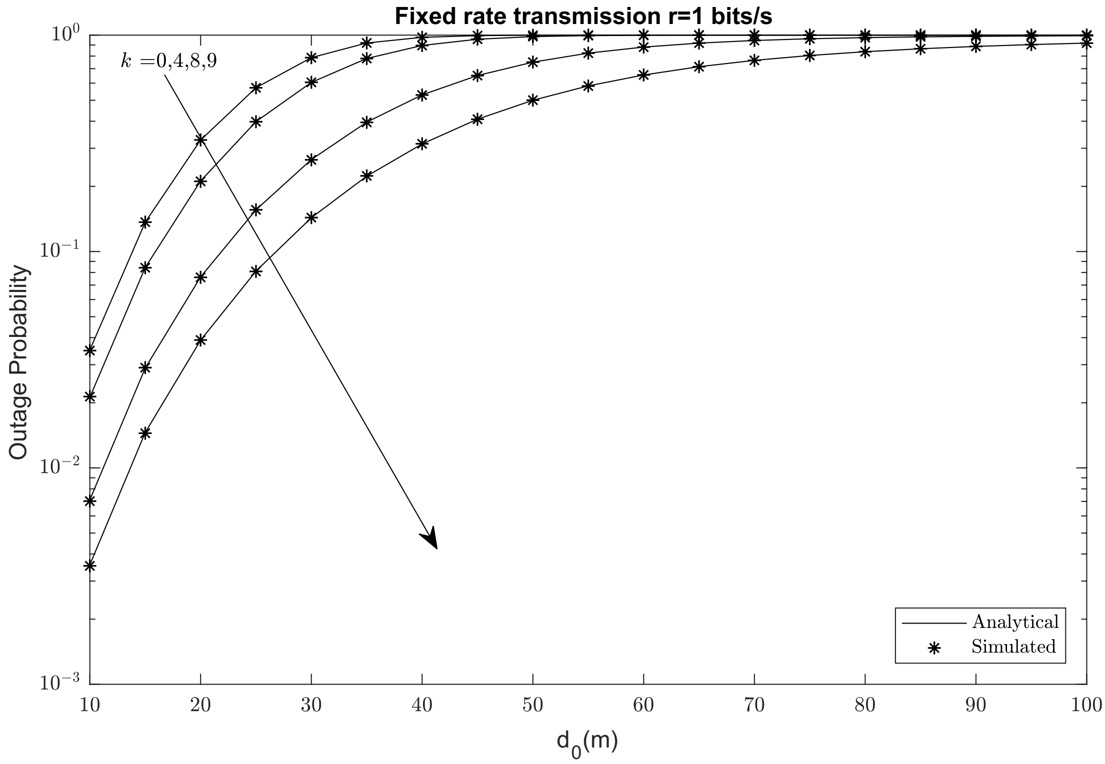

Figure 4.5: Illustration of cooperation strategy for typical distance with the fixed rate transmission and $\eta = 10$.

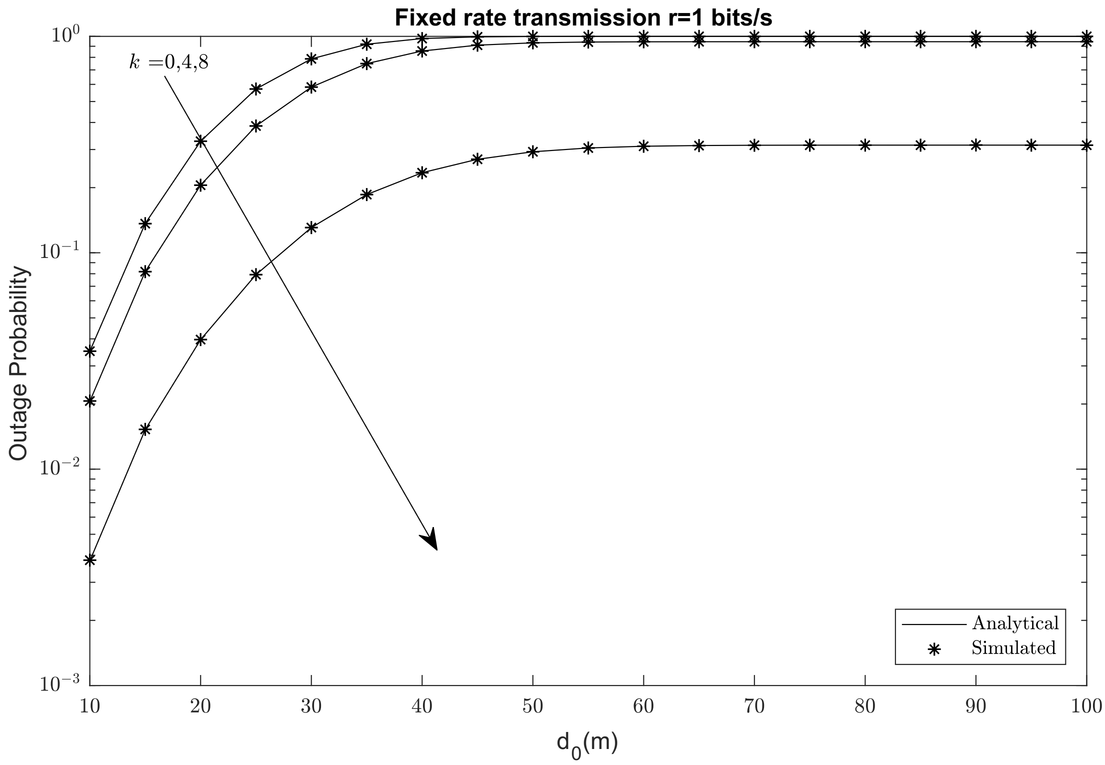

Figure 4.6: Illustration of Selection Combining strategy for typical distance with fixed rate transmission and $\eta = 10$.

4.3.2. Selection Combining

Figure 4.6, clearly illustrates that when cooperation level is increasingly limiting the interference for nearer typical link distance outage have significant improvement over the typical distance under fixed rate transmission. In the case $k = 8$ system performance can be significantly improved even for larger distance. Note that for reference link distance greater than 50 meter probability outage settles to a constant value means the condition for transmission should be at least one typical link should be nearer to UE and not far than interfering base station in a given area i.e $d_0 < d_j$.

4.3.3. Maximum Ratio Combining

In the proposed analysis, UE performs MRC schemes.

Figure 4.7 illustrates that with full interference case i.e for $k = 0$, an outage is similar to that of other schemes as there is only one link transmitting to UE, but as cooperation of RRHs is increased in case of $k = 4, 8$ there is significant improvement in outage probability even for larger typical distances.

Figure 4.8 gives clear picture of the comparison between SC and MRC scheme where the MRC schemes system performance is better than that of SC for same number of RRHs in cooperation. In case of full interference $k = 0$, both the schemes have same outage probability but as cooperation increases MRC outperform SC even for larger distance MRC has lower outage probabilities for e.g., $k = 8$.

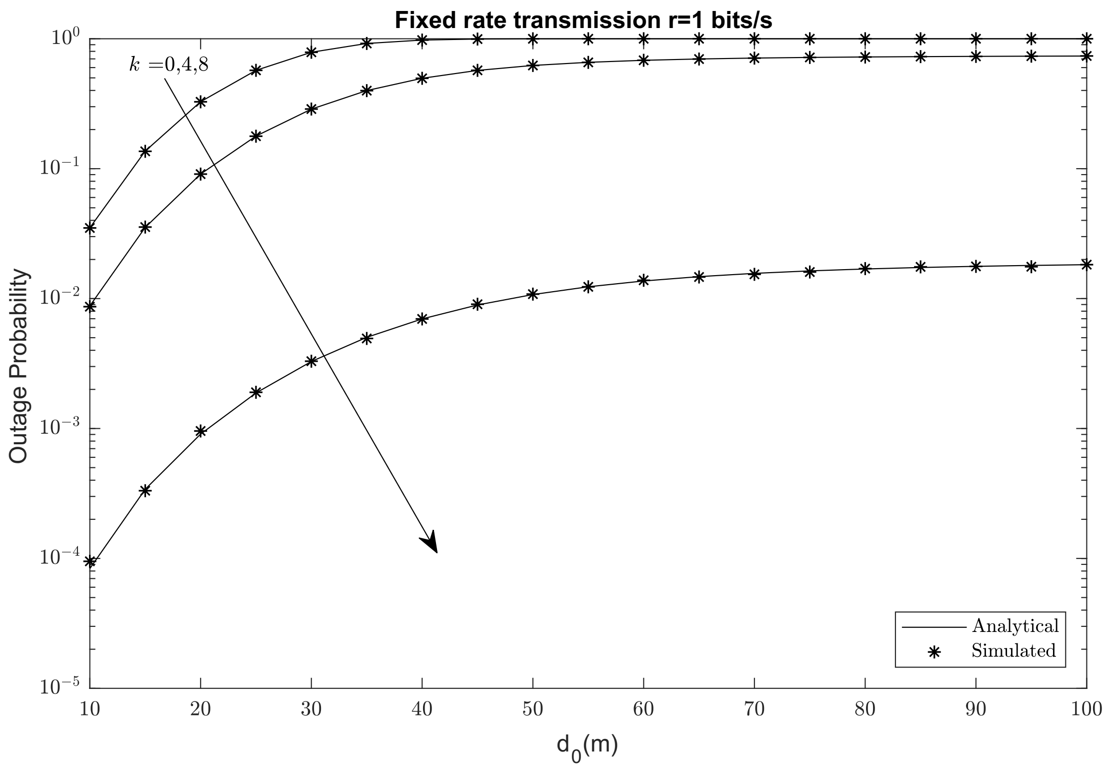

Figure 4.7: Illustration of Maximum Ratio Combining strategy for typical distance with fixed rate transmission and $\eta = 10$.

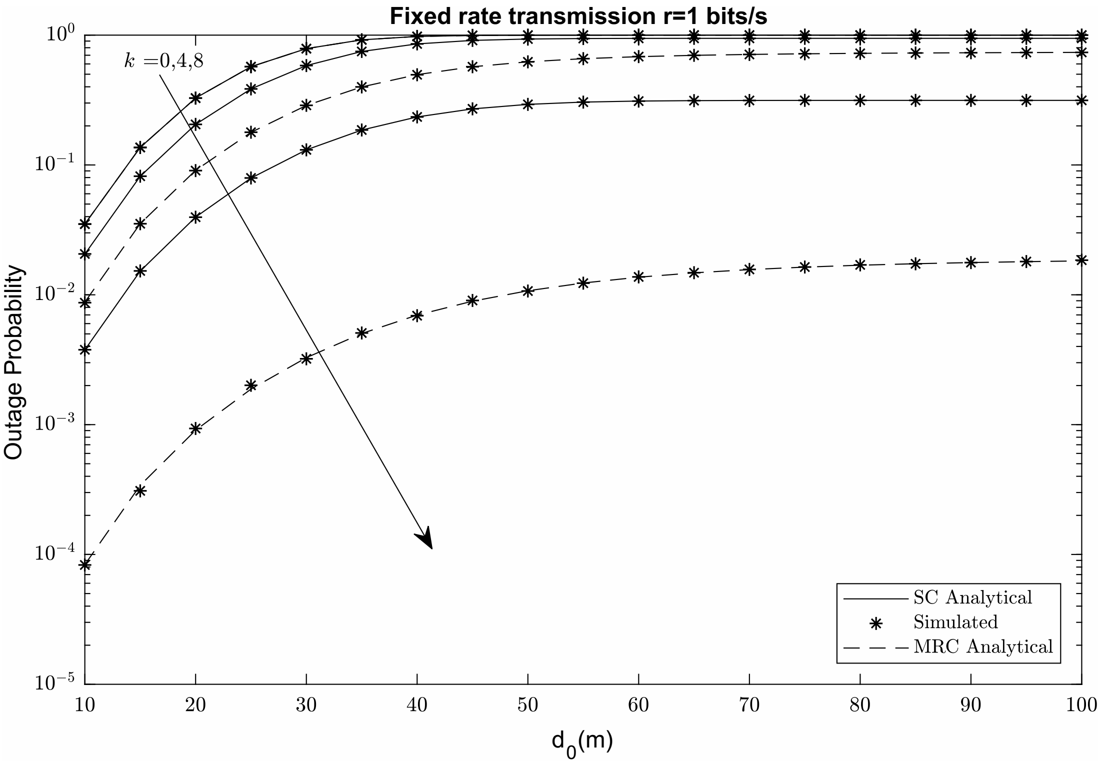

Figure 4.8: Comparative illustration of typical link distance for SC and MRC scheme for fixed rate and $\eta = 10$.

4.4. Results with Interfering link distance analysis

Herein, we assess the impact of the interfering links distances in the proposed schemes performance. For the following results we set $d_0 = 20m$, $r = 1\text{bps/Hz}$ and varying d_j from 20m to 100m.

4.4.1. Full interference and $(k - out - N)$ *cooperation*

When cooperation increases i.e. $k > 0$, out of number of base station then allowing number of RRHs to transmit limiting the interference factor system performance shows significant improvement over outage probability with respect to increasing interfering link distance which is clearly illustrated in Figure 4.9. Note that, $k = 0$ denotes full interference scenario. Clearly, as the interference distance increases the outage probability reduces.

4.4.2. Selection Combining

As cooperation $k > 0$ increases and increasing interfering link distance gives the significant improvement to reach the target outage probabilities.

Figure 4.10 gives the clear outlook to the SC schemes system performance with the interfering link distance. In the Figure, when k is increased in number the outage can be significantly improved even with the closed interfering link distances.

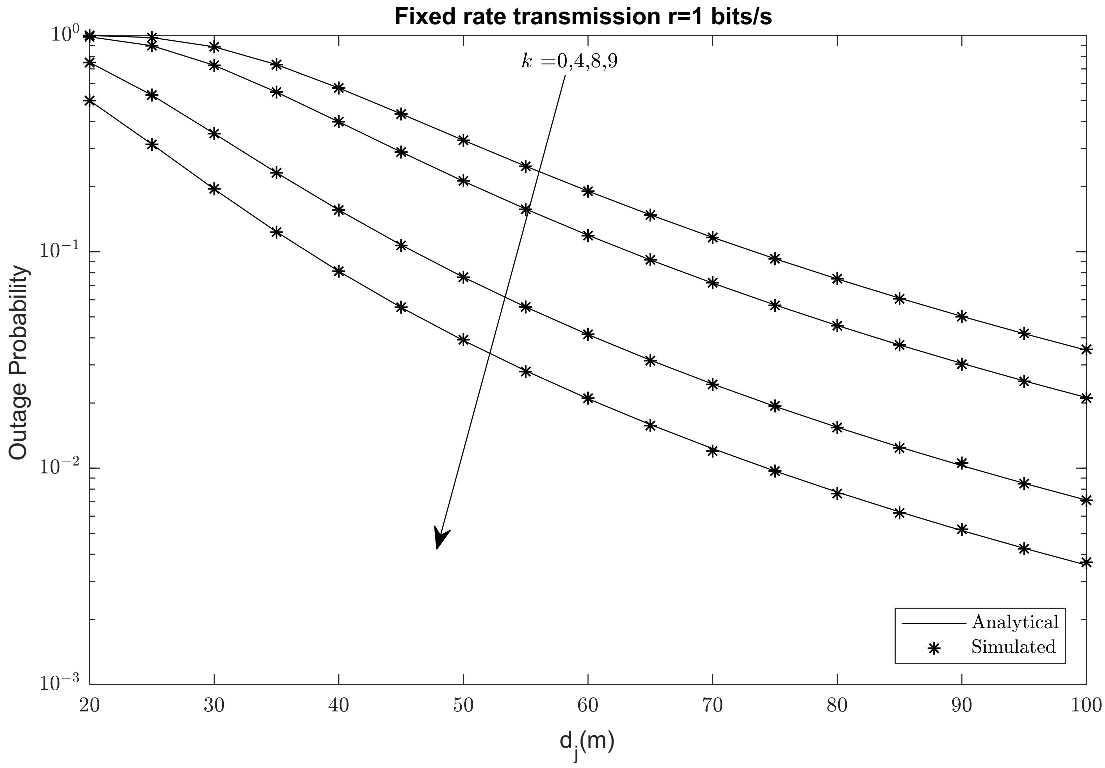

Figure 4.9: Illustration of cooperation strategy for interfering link distance with fixed rate transmission and $\eta = 10$.

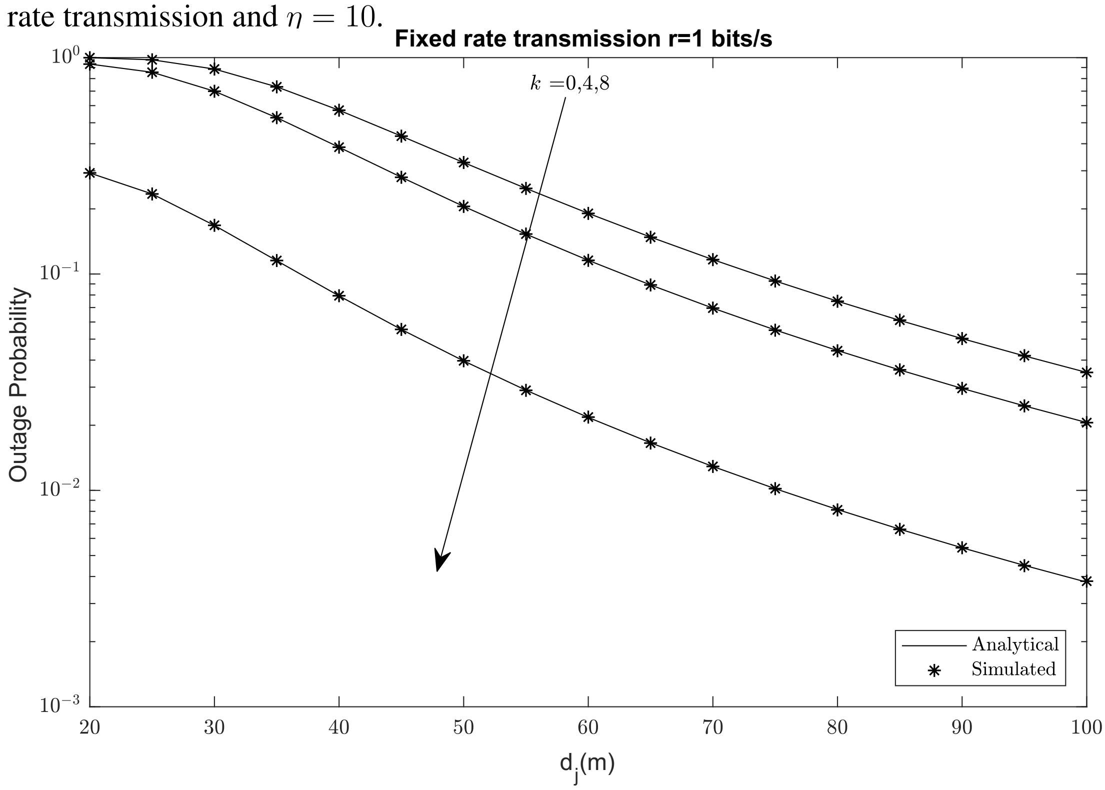

Figure 4.10: Illustration of Selection Combining strategy for interfering link distance with the fixed rate transmisson and $\eta = 10$.

4.4.3. Maximum Ratio Combining

Increasing RRHs cooperation, limiting the interference in the given area MRC scheme performs well and increasing interfering link distance can reach target outage probabilities.

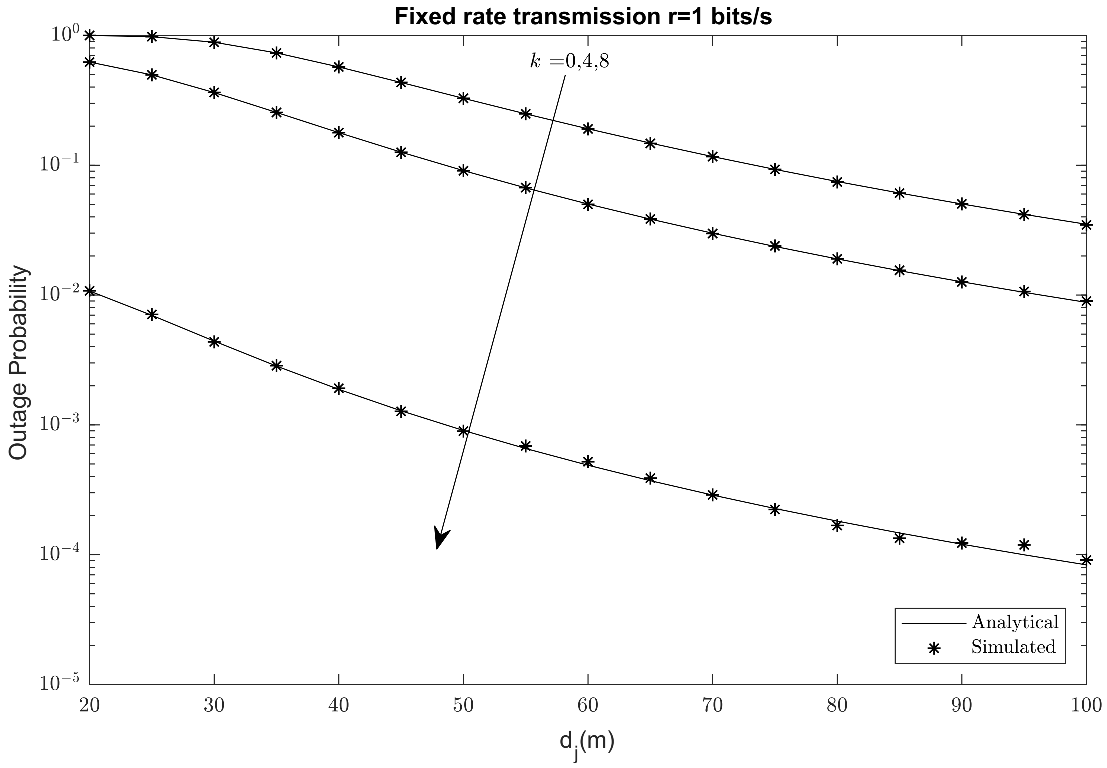

Figure 4.11: Illustration of Maximum Ratio Combining strategy for interfering link distance with fixed rate transmisson and $\eta = 10$.

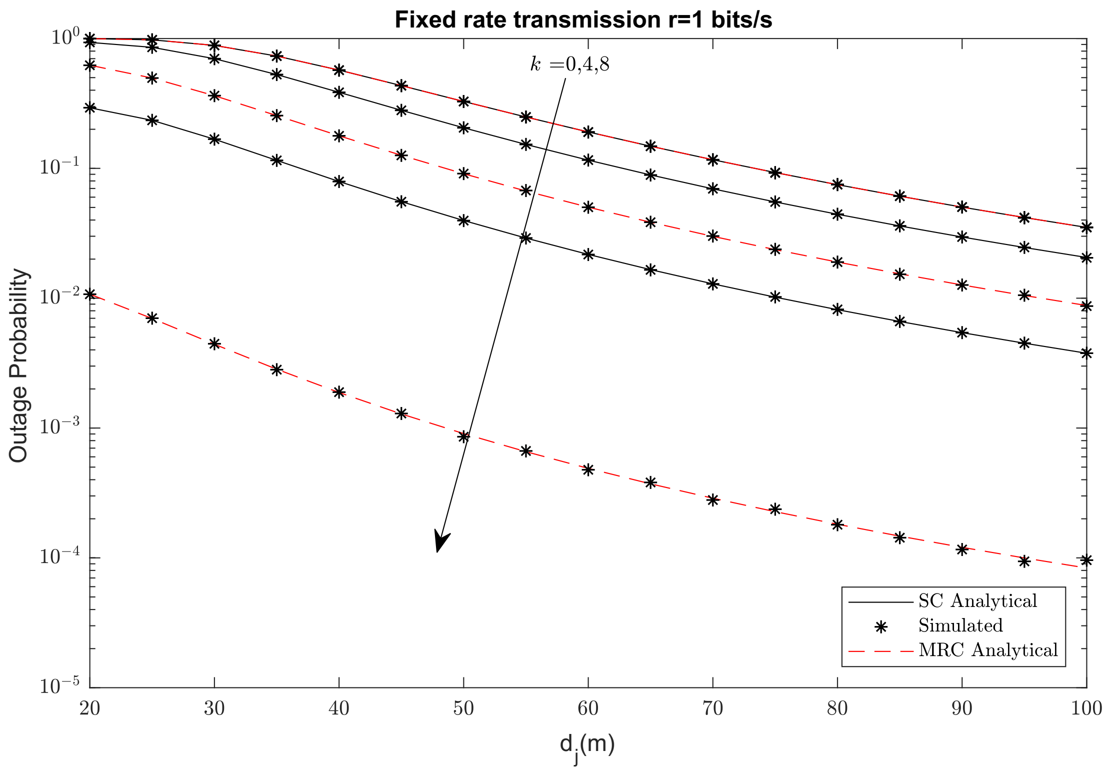

Figure 4.12: Comparative illustration of SC and MRC scheme for interfering link distance with the fixed rate and $\eta = 10$.

Figure 4.11 and 4.12 gives the clear outlook to MRC scheme and comparative analysis of SC and MRC scheme with interfering link distance. With the same cooperation gain, MRC outperforms SC scheme. Interfering link distance has also significant role in the fading and interference for the propose diversity schemes.

4.5. Results with comparative reliability analysis

In the proposed analysis, we evaluate the reliability performance of $k - out - N$ cooperation, SC, MRC schemes taking consideration of each outage from (11), (24) and (27) as detailed in Chapter 3. Reliability refers to outage probability as follows:

$$\text{Reliability} = 1 - \text{Outage Probability} \tag{29}$$

For the following results we set $d_0 = 20$, $d_j = 40$ and $r = 1\text{bps/Hz}$ and calculation of reliability is done over varying threshold (θ) SIR.

Figure 4.13, shows the reliability of the system where all the three scheme are taken into consideration and corresponding reliability analysis is done for all the scheme with $k = 0, 4, 8$ where $k = 0$ corresponds to full interference case and in this case all the scheme has the same reliability. However, as cooperation increases (limiting the interference) then reliability increases. The comparative reliability analysis of the system gives the clear outlook to meet the URLLC condition whenever UE demands URLLC services. Here, the diversity is one of the key fundamental to combat fading and thereby improving the reliability of link.

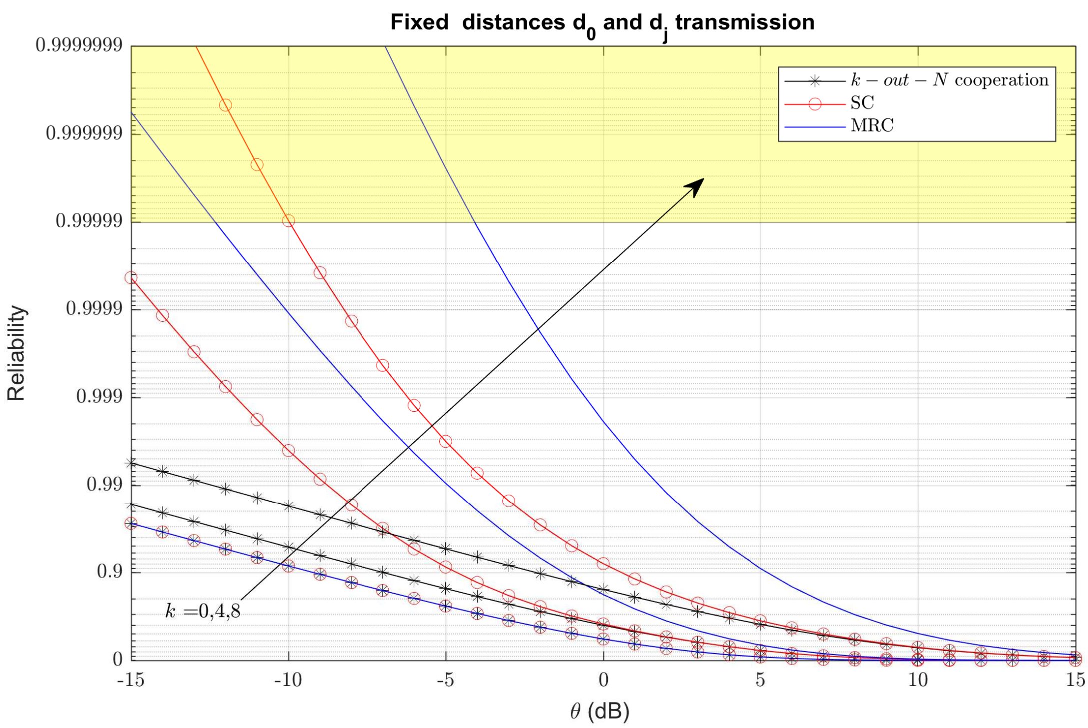

Figure 4.13: Illustration of comparative reliability analysis for Cooperation, SC and MRC scheme with the different fixed threshold θ and $\eta = 10$.

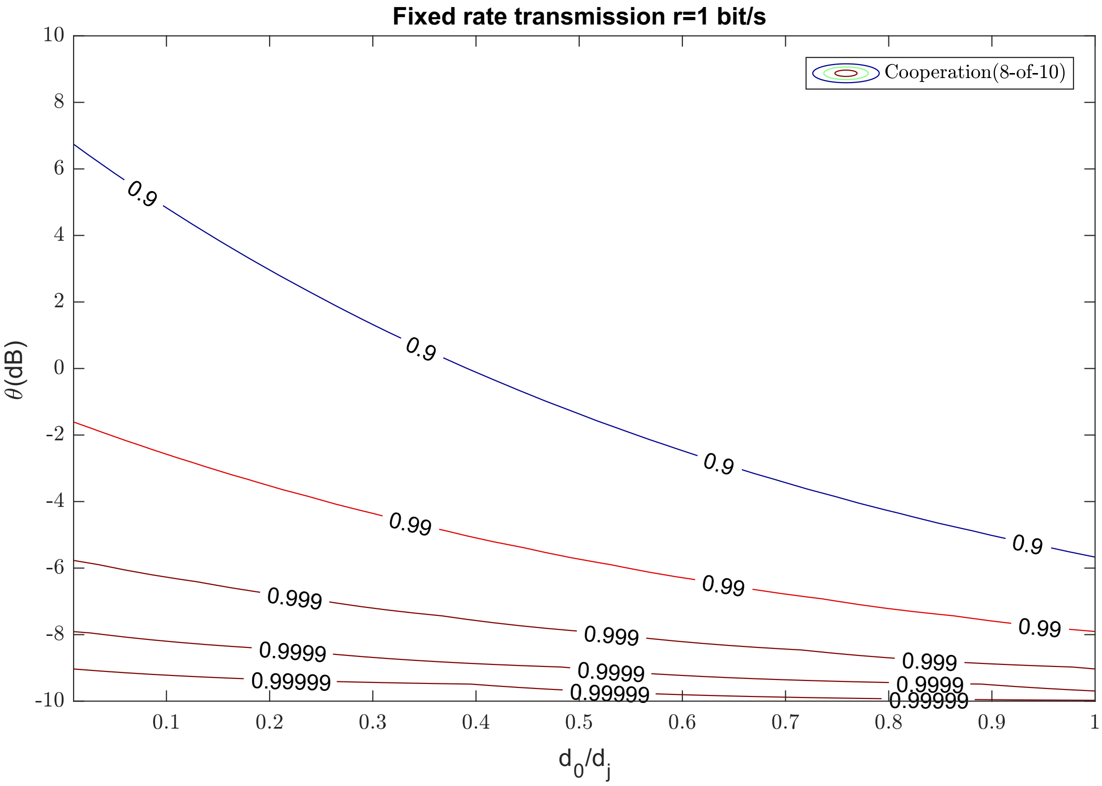

Figure 4.14: Reliability analysis of cooperation scheme with respect to distance $\frac{d_0}{d_j}$ and threshold θ.

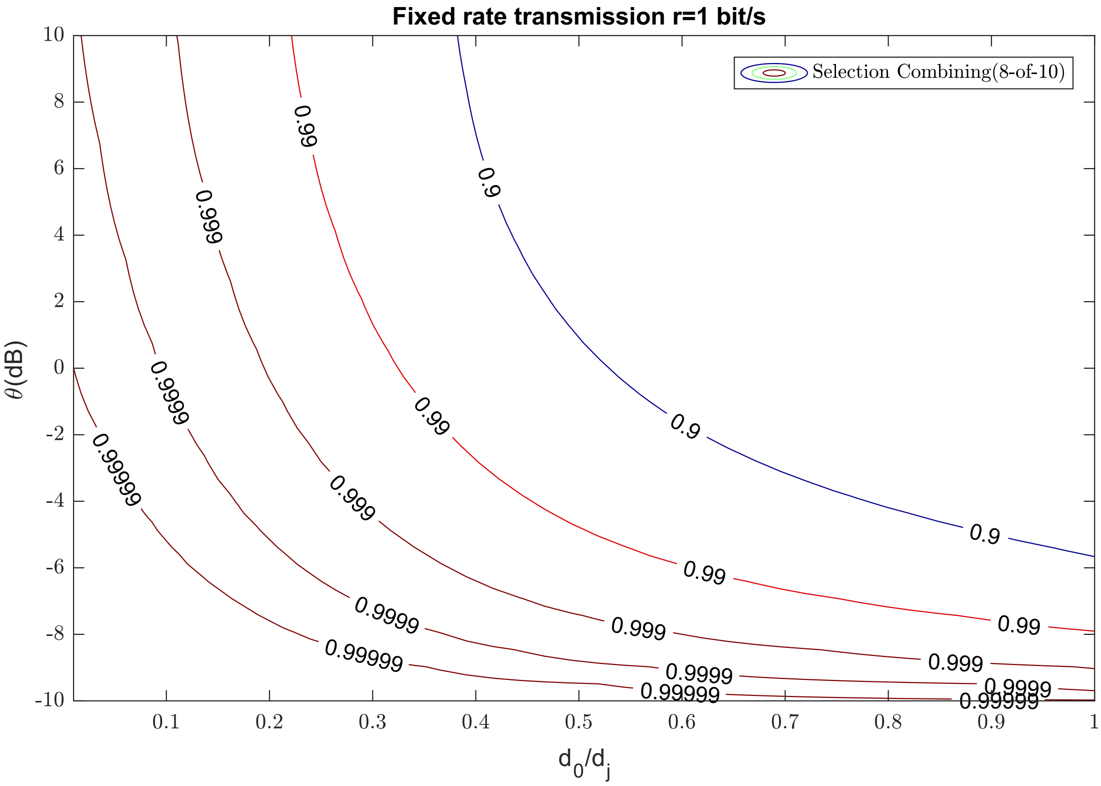

Figure 4.15: Reliability analysis of Selection Combining with respect to distance $\frac{d_0}{d_j}$ and threshold θ.

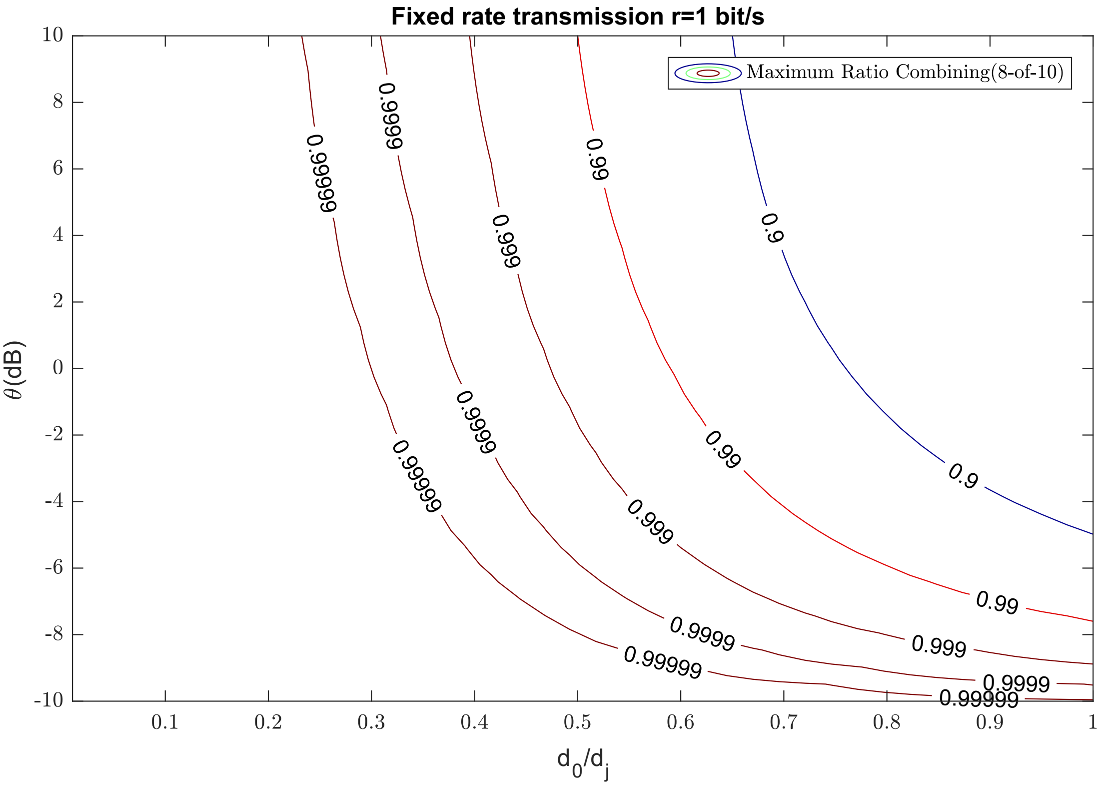

Figure 4.16: Reliability analysis of Maximum Ratio Combining with respect to distance $\frac{d_0}{d_j}$ and threshold θ.

The shaded region in Figure 4.13 represents the ultra reliable region of operation in URLLC as mentioned by some standardization bodies which clearly shows that even with $k = 4$ RRHs in cooperation with MRC schemes deployment by UE can reach URLLC target. So, the diversity gain from MRC is superior than that of SC schemes. Although, other schemes trend analysis shows with more RRHs in cooperation can reach the URLLC target.

Figure 4.14, 4.15 and 4.16 are the contour plot with respect to ratio of typical distance to interfering distance and threshold SIR. The proposed analysis is done with fixed rate transmission and for all three schemes Cooperation, SC and MRC. The following result has $k = 8$ RRHs in cooperation. Figure shows that with same value of threshold and distances, MRC scheme easily achieves reliability target of five 9's than that out SC and MRC. For e.g., cooperation schemes attains reliability target at lower threshold while SC has some higher threshold for same target reliability. But, from MRC system gain shows superiority among the schemes as it reaches the target reliability for higher threshold and with a greater ratio of $\frac{d_0}{d_j}$.

5. CONCLUSION

In the future, many critical applications like factory automation, smart grid, e-health, V2V, V2X demand for high reliability and low latency which poses many technical challenges when designing the wireless systems. These MTC applications are a key enabler of URLLC in upcoming 5G networks. Wireless communication technologies have set the goals to deliver this vertical of services in future 5G networks.

The main goal of this thesis was assessed the performance of a MTC network under URLLC requirements and how is it possible to deliver the services with ultra-reliability. To do so, we resort to diversity and multi-connectivity. The system is analysed considering Rayleigh fading channel with path loss exponent α and consist of one typical link RRH which is close to UE and number of interfering RRHs which are equidistant with UE. UE consist of single antenna and all RRHs are also equipped with single antenna and it is analysed considering that UE operates with full interference, cooperation ($k - of - N$), where k RRHs are active and the remaining other are in silence mode, SC and MRC schemes when cooperative RRHs are also forwarding the message with their respective closed-form derivation are also clearly shown in Chapter 3.

We provide numerical results and discussion by showing outage probability and reliability analysis of schemes when varying different dependent parameter such as SIR threshold, typical link distance, interfering link distance. The numerical results show the outstanding performance of MRC scheme and also the feasibility of ultra-reliability operations when the number of RRH's or connectivity increases at UE. In case of moderate reliability with same number of connectivity or RRHs at UE side cooperation ($k - of - N$) and SC schemes also reached the feasibility of ultra reliable region of operations. Finally, we validate analytical results via Monte Carlo simulations.

As future work, and as discussed in Chapter 3, the cooperative, SC and MRC schemes require some sort of coordination, which is handled by C-RAN and the expected processing delay is low, thus enabling power control and rate adaptation schemes. We aim to consider Joint Decoding (JD) and assess their performance compared to the proposed methods accounting for possible overheads and system complexities. As mentioned in Chapter 4, we also aim to look at more resource and time efficient Monte Carlo methods for simulations of the five 9's reliability targets, since standard Monte Carlos methods are extremely time-consuming for such URLLC scenarios. Multi-connectivity with MIMO at RRHs side can also be considered in future analysis.

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