A FRAMEWORK FOR ULTRA RELIABLE LOW LATENCY MISSION CRITICAL COMMUNICATION

A THESIS IN
Electrical Engineering

Presented to the Faculty of the University of
Missouri—Kansas City in partial fulfillment
of the requirements for the degree

MASTER OF SCIENCE

By
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Kansas City, Missouri
2017

A FRAMEWORK FOR DEVELOPMENT OF ULTRA RELIABLE LOW LATENCY TECHNIQUES FOR MISSION CRITICAL COMMUNICATION

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ABSTRACT

Mission-critical communication is one of the central design aspects of 5G communications. But there are numerous challenges and explicit requirements for development of a successful mission-critical communication system. Reliability and delay optimization are the two most crucial among them. Achieving reliability is influenced by several difficulties, including but not limited to fading, mobility, interference, and inefficient resource utilization. Achieving reliability may cost one of the most critical features of mission critical communication, which is delay. This thesis discusses possible strategies to achieve reliability in a mission-critical network. Based on the strategies, a framework for a reliable mission-critical system has also been proposed. A simulation study of the effects of different pivotal factors that affect communication channel is described. This study provides a better understanding of the requirements for improving the reliability of a practical communication system.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering have examined a thesis titled "A Framework for Development of Ultra Reliable Low Latency Techniques for Mission Critical Communication," presented by Shubhabrata Mukherjee, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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LIST OF ACRONYMS AND ABBREVIATIONS

AWGN: Additive white Gaussian noise

BER: Bit error rate

BPSK: Binary phase shift keying

FER: Frame error rate

LTE: Long term evolution

M2M : Machine to machine

MIMO: Multiple input and multiple output

MCPTT: Mission critical Push To Talk

OSTBC: Orthogonal space time space time block code

PTT: Push To Talk

QPSK: Quadrature phase shift keying

SNR: Signal to noise ratio

UE: User equipment

URC: Ultra reliable communication

URLLC: Ultra reliable low latency communication

ACKNOWLEDGEMENTS

I would like to take this opportunity to express my deep gratitude to my advisor and mentor Dr. Cory Beard for all his guidance during the project. I thank him for all the encouragement he had given me to finish the project successfully. I appreciate his continuous support and his useful critiques.

I would also like to extend my gratitude to my thesis committee Dr. Ghulam M. Chaudhry & Dr. Ahmed Hassan for their precious presence.

I would like to thank my father Lt. Mr. Sandipan Mukherjee and my mother Mrs. Bulbul Mukherjee for their sacrifice and continuous support.

I would like to thank University of Missouri – Kansas City for giving me this wonderful opportunity.

CHAPTER 1

INTRODUCTION

Emergency circumstances like fire, terror attack, earthquake, outbreak of infectious diseases, or chemical spills which require immediate attention from first responders can be considered as mission critical conditions. The traditional push-to-talk or broadcast radios do not incorporate modern smartphone technologies, so are not suitable for handling current situations as efficiently and swiftly as possible. Hence, the 3GPP decided to include mission critical push-to-talk (MCPTT) or new generation mission critical communications as a crucial criterion of LTE Rel. 13 and onwards. The primary responsible working group SA6 [24] is designated to finalize the standardization for this. A U.S. nationwide network for first responders called “FirstNet” was formed from the public safety and advisory committee or PSAC [23] consisting of members from all parts of the public safety community to assist FirstNet in its operation. This paper mainly focusses towards developing a simulation-based modeling approach that attempts to combine the primary criterion for development of a future-oriented mission-critical communication system. This paper emphasizes how to optimize two main prerequisites of a MCPTT, reliability and delay.

1.1. Reliability in Communication

1.1.1. Definition

The ability to perform a required function under stated conditions for a stated period. Reliability is expressed as a probability from 0 to 1. Assuming the system was operating at time zero, Reliability is the probability that it continues to operate until time t.

1.1.2. URLLC

URLLC or ultra-reliable low latency is to fulfill the conflicting requirement of added reliability (up to five 9’s 99.999) and minimized delay.

1.1.3. Reliability Factors

Power decay of the signal due to fading, mobility, etc. Increased interference from devices resource depletion due to competing devices in a random access, downlink congestion, etc. Protocol reliability mismatch captures where the protocols operate as expected where the control messages are reliably transferred. But control messages are commonly not adaptive to seriously worsened communication conditions. AWGN is the most commonly used model, don’t support detailed temporal & spatial variation. Pathloss is deterministic, at smaller time scale only for high mobility but shadowing – for different terrain profile & multipath fading- for multi-path propagation, are stochastic, can change in mili or micro seconds.

1.1.4. Reliability Analysis

Reliability study is mainly difficult because effective link qualities are time variant. An efficient approach is to take opportunistic URC based on sending data when link is in a good condition. A structure for modeling, prediction and analysis the theoretical reliability of the based-on fading, mobility, interference etc. can be given based on the part stress method (1), assuming time dependent factors as elements/components and their respective Transmission Times to Failure (TTTF). Other techniques like (2) Fault Tree Analysis & (3) accelerated testing also exists to improve the components. For automotive industry safety is a major concern so is reliability, started by EU (METIS)

1.1.5 Reliability Analysis Methods

1.1.5 (a) The Part Stress Analysis method is used most time and is applicable when the design is near completion and a detailed parts list, or BOM, plus component stresses are available. It is based upon the idea that the more components that there are in the system, and the greater stress that they undergo in operation, the more often they will fail.

1.1.5 (b) A Fault Tree analysis is a graphical representation of events in a hierarchical, tree-like structure. It is used to determine various combinations of hardware, software, and human error failures that could result in a specified risk or system failure. It relies Boolean logic and Probability Theory. Boolean logic reduce the Fault Tree structure into the combinations of events for failure. Probability Theory used to determine probabilities that the system will fail during a particular mission.

1.1.5 (c) **Accelerated testing** is the process of testing a product by subjecting it to conditions (stress, strain, temperatures, voltage, vibration rate, pressure etc.) in excess of its normal service parameters in an effort to uncover faults and potential modes of failure in a short amount of time. By analyzing the product's response to such tests, engineers can make predictions about the service life and maintenance intervals of a product.

1.1.6 Mission Critical Push-To-talk (MCPTT)

The phrase “mission-critical push-to-talk” refers to a PTT product functionality that meets the requirements of mission-critical voice communication, which include high reliability, low latency, support for group calls and 1:1 calls, talker identification, device-to-device direct communications, emergency calling, clear audio quality, etc. The term “MCPTT” is now typically used to refer to 3GPP’s “Mission Critical Push to Talk (MCPTT) over LTE” standard, which is part of 3GPP Release 13 & 14.

1.1.7 FirstNet:

FirstNet is the nationwide public safety network based on LTE commercial standards. It standardizes additional requirements for reliability, security & massive mobile device supporting capability.

1.1.8 Requirement for MCPTT Voice:

- Direct & talk Around Mode (off network communications).
- Push-to-Talk (PTT) with low latency.
- Full Duplex Voice (commercial/PSTN calls).
- Group Call (one to many communication broadcast)
- Talker Identification
- Emergency Alerting (highest level of priority)
- Clear audio Quality

1.1.9 Role of URLLC in 5G communication:

- Factory Automation
- Motion Control
- Smart Grid Process
- Automation
- Intelligent Transportation Systems
- Tactile Internet

CHAPTER 2

RELATED WORKS

Petar Popovski is the pioneer in the field of ultra-reliable communication system analysis. In his several articles, he discussed ultra-reliable communications, low latency using short packets, massive machine-to-machine (M2M) communications and using resource pooling techniques to achieve ultra-reliable low latency communication (URLLC) [2-7]. Articles [17-19] mainly discuss economic feasibility and cost optimization for designing reliable communication networks. Papers [20-22] discuss probabilistic approaches like outage analysis and prediction algorithms, using state model and availability indicators for modeling reliability of a network, and [9] discusses the design of a practical reliable communication system using textile antennas. Most articles discuss analytical modeling of reliability of a network from various aspects or mainly performed feasibility studies of constraints to build a practical reliable communication system. However, an overall theoretical or simulation design model of a reliable communication system has not been immensely used. This paper discusses more of a modular and block based approach to show a likely design idea of a future proof ultrareliable and low-latency network. It also uses an existing model from MATLAB, designed by Mathworks team [1], to show some practical implications of combining two or more reliability controls like diversity and coding mechanisms.

CHAPTER 3

CASE STUDIES FOR MISSION CRITICAL COMMUNIICATION

3.1 Attack on the Pentagon, Washington DC, September 2001:

On 11 September 2001, a plane piloted by terrorists crashed into the Pentagon Buildings in Washington DC. During the height of the response to this disaster, cellular communications in the region were ineffective and unresponsive. Verizon experienced fifty to one hundred percent more traffic than normal throughout America on its network. Cingular Wireless, the second largest wireless communications carrier, experienced a four-hundred percent increase in the number of attempted calls in the DC Metropolitan District. Adding to this problem was an overwhelming demand on the PSTN, which served as a backbone connectivity to the cellular networks. Because of the numerous service demands, users, including those from the Emergency Services, experienced call delays, interruptions and busy tones.

To improve and support mobile communications for the disaster management, the mobile service providers deployed Cellular On Wheels (COW) to the Pentagon and distributed mobiles to public safety personnel. It was reported that Nextel's Direct Connect feature and two-way text messaging services worked while its cellular service failed during the initial response to the disaster. Direct Connect is a two-way radio service between phone users. Neither Direct Connect nor the two-way messaging services are dependant on the PSTN, which greatly aided the reliability and availability of these services. The only reliable and sustainable communication system for the Emergency Services was their own PMR systems.

The report for the Public Safety Wireless Program (PSWN) entitled 'Answering The Call: Communication Lessons Learned From The Pentagon Attack' states:

> Major incidents, regardless of location, have shown that commercial service networks are not designed to handle the immense volume of calls generated at or near an incident scene. Responders found that the only reliable form of communication were their own private Land Mobile Radio Systems. The Nextel Direct Connection was an exception.

The report makes various communication findings and recommendations, including:

- Making plans for Priority Access Systems (PAS) for Government and public safety officials on the cellular networks during disasters
- Development of regional/state-wide communication systems to reduce interoperability issues
- Adherence of common technology standards in the design, procurement and implementation of future public safety communication systems.

3.1.1 Sprint UE Relay by Nokia

Sprint UE Rely is a classic example of an industrial use of reliable communication. Sprint is making use of their existing 2500 MHz by its small cell called mini-macro. These small cells mainly use the existing macro cell network as a backhaul. These cells act like Wi-Fi hotspots, the only difference is instead of sending a Wi-Fi signal, the relays send LTE signals.

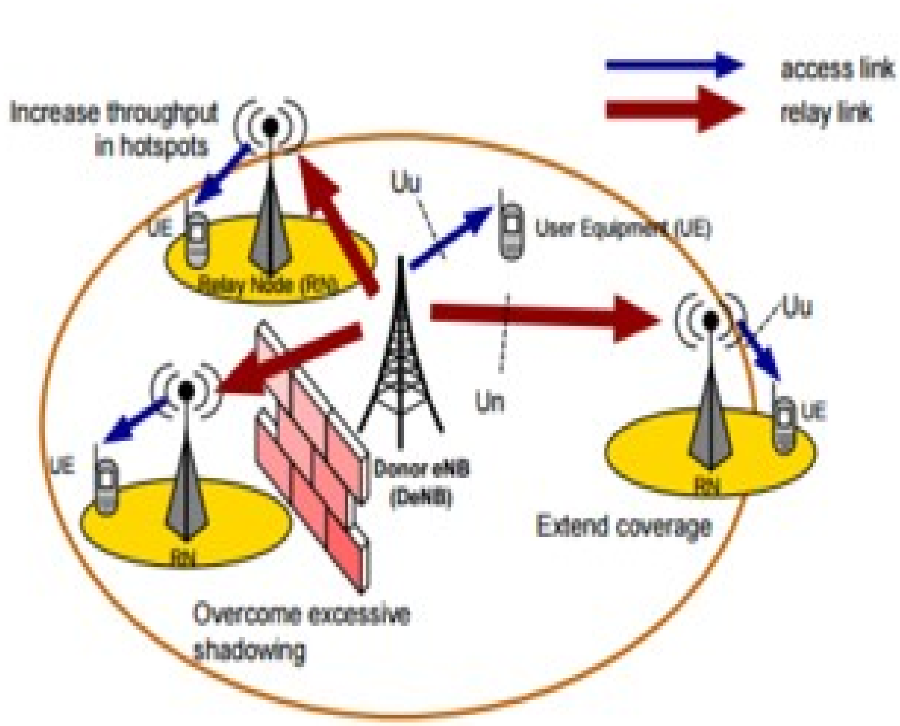

Figure 1. Sprint UE Relay by Nokia

Details:

These UE Relays are basically user equipment (like mobile handset), with some added capability. They are having their own IMEI number just like any UE. Once it receive LTE signal from main enodeB, it get connected to the main LTE network. There is physical cable or Bluetooth connectivity with a small enodeB (called mini-macro), which acts like a small cell. Once UE Relay receives the LTE signal, adjacent mini-macro also receive signal from it and start radiating. UE Relay also having its own error correction and signal boosting mechanism. So, even if it receives a low-quality signal from macro, mini-macro can radiate a better and crispier LTE signal to the nearby users, which comes under its small cell network.

Advantages:

- These mini macro's do not require any additional infra & backhaul set-up like a traditional macro, it can use existing macro network for these purposes.
- As previously mentioned, UE Rely has its own error control and signal boosting mechanism so, users get a stronger & crisper signal.
- Relatively low coverage area, where traditional macro network setup is difficult can be connected relatively with very less cost.

Disadvantages:

- During heavy traffic in busy hours, the whole network may get congested due to bandwidth sharing, hence the existing macro user may get affected.
- Maximum speed of any mini macro user is limited by the maximum capacity and coverage available to the donor macro enodeB.

CHAPTER 4

STRATEGIES TO ACHIEVE ULTRA-RELIABLE M2M

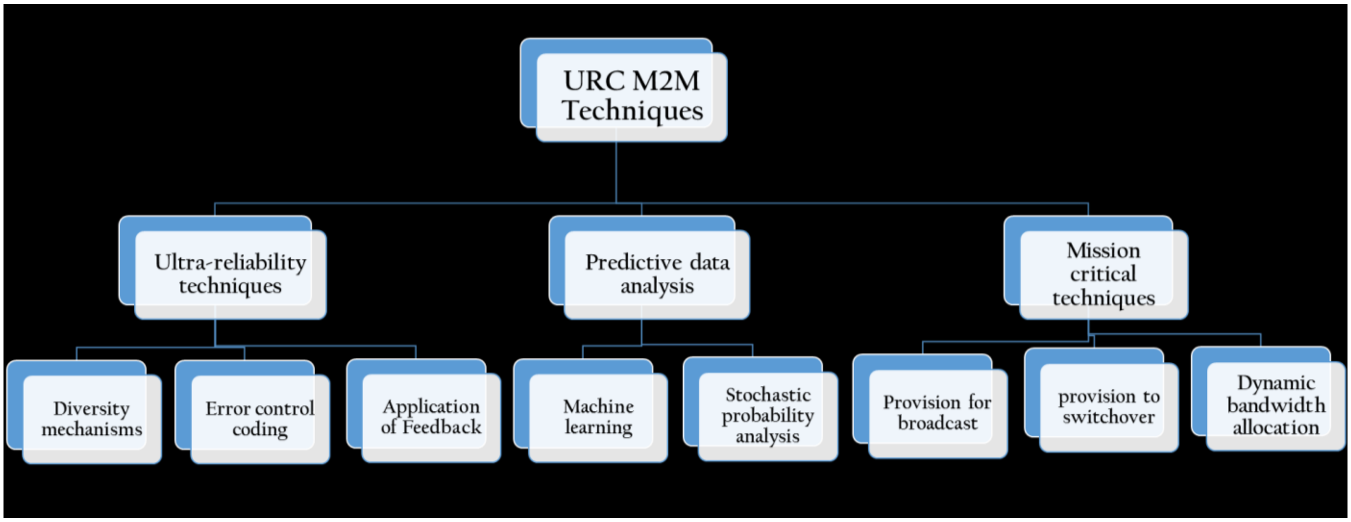

Figure 2. Techniques for ultra-reliable communication

The over-the-air interface for M2M communication experiences several challenges. Fading and interference are the primary concern for reliable data transmission. Deploying error control mechanisms add extra delay to the system. And efficient utilization of existing resources is one of the major challenges for any M2M network that is designed for a mission-critical operation. Several techniques can be tested to combat the existing challenges. We can divide approaches of end-to-end ultra-reliable communication mainly into 3 categories:

- Ultra-reliability techniques: These mainly includes diversity mechanisms, dynamic bandwidth allocation, and the application of Feedback.
- Predictive data analysis: This approach includes the use of machine learning and stochastic probability analysis methods.
- Mission critical techniques: Provision for broadcast and provision to switchover between priorities of communication.

4.1 A Proposed Framework for an Ultra-Reliable Low Latency Communication

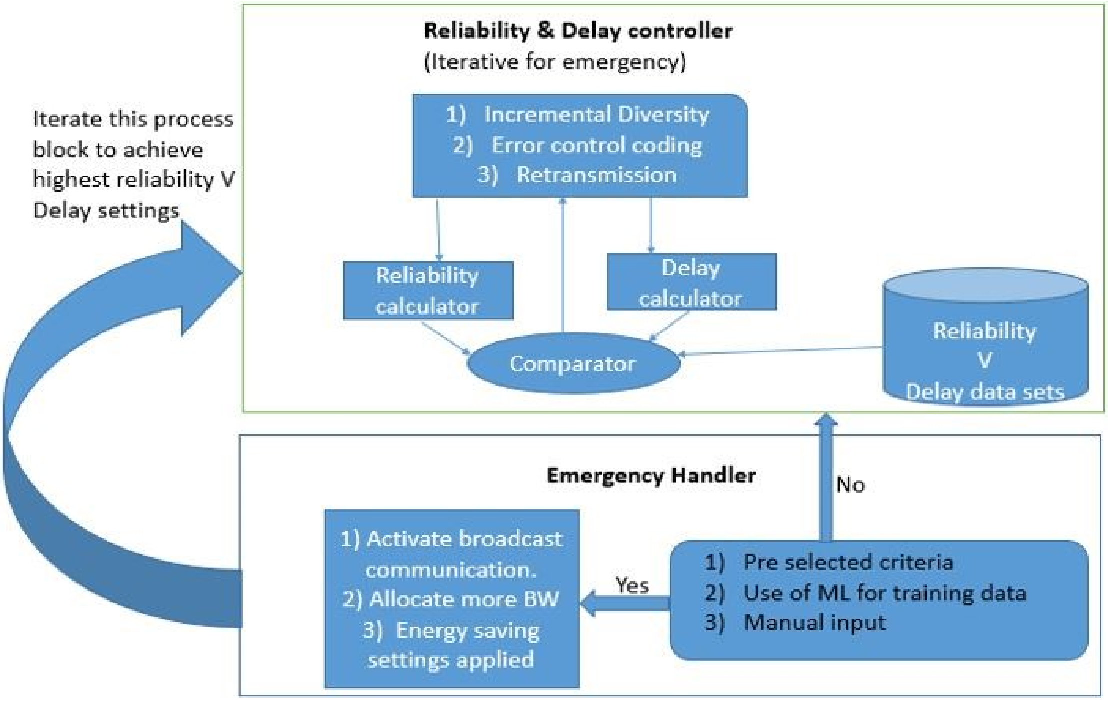

Figure 3. The proposed model for ultra-reliable low-latency communication

Based on the existing techniques to achieve an “Ultra Reliable Low Latency Communication” as shown in Fig. 1, a framework for URLLC is described in this section. A simulation study and results for a sub-system of the model are shown in the next section. The proposed URLLC system model is shown in Fig. 2 and is divided mainly into two sections, (A) a Reliability and Delay Controller System and (B) an Emergency Handler. The controller section is the main part of this architecture, whereas the Emergency Handler section is designed specifically to enable mission critical communication services options.

4.1.1 Controller Section:

The controller section consists of 5 main sub-systems. The function of each sub system described below:

4.1.1 (a) Reliability calculator:

The Reliability calculator computes the overall system reliability using event-based calculations or part stress analysis methods. It receives its input from the reliability control block and the output is fed to comparator.

4.1.1 (b) Delay calculator:

This sub-system is used to calculate the overall delay of the system. This is also fed by the reliability control block and the results are fed back to the comparator.

4.1.1 (c) Reliability controller:

This section is the heart of the system. The Reliability controller is equipped with three different measures to control reliability: Incremental Diversity, Error control coding and Retransmission. These techniques can be applied independently, as well as any two of them, and even all of them together to achieve the highest reliability. The effect of these controlling parameters on the system is discussed in detail in experimental results section.

4.1.1 (d) Reliability vs. Delay data sets:

This section is the main storage for reliability and delay data collection. It is comprised of results collected from past events, data obtained from simulation results, and optional inputs. This is the main tool used by the Reliability and Delay controller iteratively or non-iteratively to calculate the overall system performance in terms of reliability and delay.

4.1.1 (e) Comparator:

This is the decision-making block in the system. It uses data sets received from the data set block as a reference for comparison and receives its input from two of the calculation sections. After each comparison, it feeds its results to the reliability controller section which then uses the outcome of decision to adjust settings. Like other blocks in the system, this is also capable of multiple iterations.

4.1.2 Emergency Handler:

The second part of the system, i.e. the Emergency Handler section is comprised mainly of two subsections, as described below:

4.1.2 (a) Emergency selector:

This is the subsystem which decides the overall system flow and can be iterative or non-iterative. We mainly use three techniques for better estimation. Firstly, we use a set of predefined criteria to trigger emergencies and multiple iterations of the RDC (reliability and delay controller) block. Secondly, the block uses a set of machine learning techniques, obtained from predictive data analysis. And finally there is an option to trigger an emergency mechanism using human intervention, which enables taking manual inputs

4.1.2 (b) Emergency initiator:

This section is designated specifically for ultra-reliable low latency, mission critical communications. It mainly deploys three functions, epically used during emergency, those are:

1. Activation of broadcast communication mode – During an emergency, any critical communication requires efficient exchange of voice, data, multimedia between first responders and emergency group members. Hence, broadcast mode is a preferred mode of communication, as seen from traditional MCPTT communications as well.
2. Allocation of additional bandwidth – During any emergency, insufficiency of resources is a crucial problem to address. This technique allows extra3. Allocation of resources to mission-critical specific applications. It also has an option of restructuring the

resource allocation grid and sharing bandwidth from comparatively low priority applications.

3. Activation of energy saving mode – Energy saving is another critical requirement for any communication with limited amount of energy sources. As an example, for sensor networks deployed in remote areas this is a vital requirement. Like the other two functionalities, this also can be controlled based on the type of emergency communication that is being operated.

CHAPTER 5

Adaptive MIMO System with OSTBC

5.1 Orthogonal space-time block code (OSTBC)

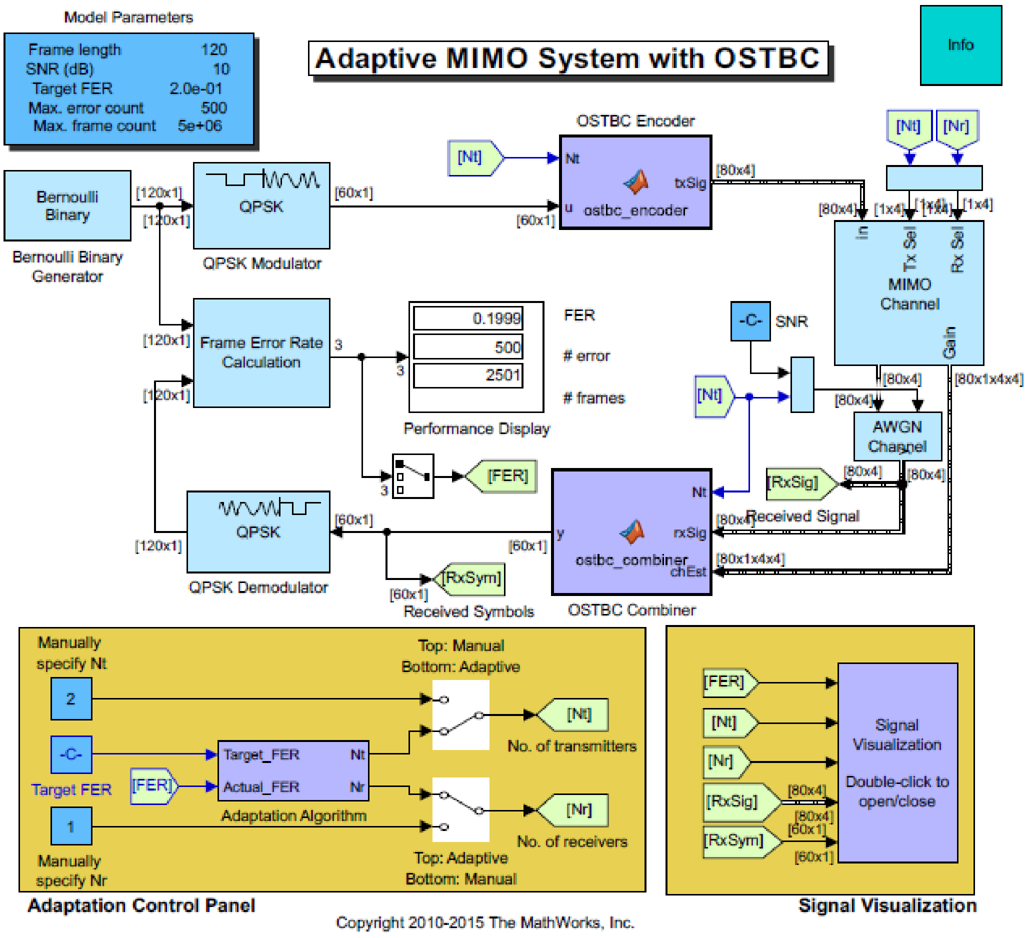

Figure 4. Adaptive MIMO System with OSTBC © 2010 –2015, The Math works Inc.

OSTBC or Orthogonal Space-Time Block Codes is a recent error control coding approach. In this model OSTBC Encoder encodes the symbols that comes from the QPSK Modulator. Either the Alamouti code for two transmit antennas or other complex orthogonal codes used for three or four total transmit antennas. The number of transmit antennas which is user defined, given to this block as an input. The output of this block is an (Ns x Nt) variablesize matrix. The number of columns (Nt) corresponds to the number of transmit antennas and the number of rows (Ns) corresponds to the number of orthogonal code samples transmitted over each transmit antenna in a frame. This block is a MATLAB Function block that uses the comm. OSTBC Encoder System object to implement the encoding algorithm for selected transmit antennas.

CHAPTER 6

SIMULATION RESULTS:

The effect of functions for increasing reliability of the system deployed by the RDC block is described with simulations of a practical communion channel. The communication in a practical channel is affected by several factors like, fading, interference etc., hence the Rayleigh distribution is used to demonstrate the behavior of a lossy communication channel.

6.1 Incremental Diversity

We considered mainly three scenarios, the first is without any diversity, (1 Transmit, 1 Receive), second one is using 2 Transmit antennas and 1 receive antenna, i.e., Alamouti configuration, and finally for the third scenario we used 1 transmit 2 receive antennas, i.e., a Maximal ratio combining procedure. In Fig. 3, we have shown the degradation of the communication channel for all the three scenarios. The characteristics in Fig. 3 show the somewhat linear (on a log-log scale) relationship between higher power and the decrease in BER. And as the channel condition degrades, the reliability keeps decreasing even if we achieve higher SNR. But when we use higher order diversity, we can achieve higher reliability in terms of BER, for comparatively lower SNR, when the channel condition degradation occurs.

Table 1: Effect of 1X1 MIMO on channel quality degradation in terms of Frame Error Rate

MIMO configuration type	**SNR(in dB)**	**Max error**	**FER value achieved in 1X1 MIMO**
1X1	10	50	0.373134328
1X1	12	50	0.318471338
1X1	14	50	0.279329609
1X1	16	50	0.171232877
1X1	18	50	0.132978723
1X1	20	50	0.09487666
1X1	22	50	0.063938619

Table 2: Effect of 1X2 MIMO on channel quality degradation in terms of Frame Error Rate

MIMO configuration type	**SNR(in dB)**	**Max error**	**FER value achieved in 1X2 MIMO**
1X2	10	50	0.240384615
1X2	12	50	0.174825175
1X2	14	50	0.137362637
1X2	16	50	0.125628141
1X2	18	50	0.095419847
1X2	20	50	0.019447686
1X2	22	50	0.002803634

Table 3: Effect of 2X2 MIMO on channel quality degradation in terms of Frame Error Rate

MIMO configuration type	**SNR(in dB)**	**Max error**	**FER value achieved in 2X2 MIMO**
2X2	10	50	0.135501355
2X2	12	50	0.092764378
2X2	14	50	0.063371356
2X2	16	50	0.002350176
2X2	18	50	9.94E-04
2X2	20	50	1.47E-04
2X2	22	50	2.34E-05

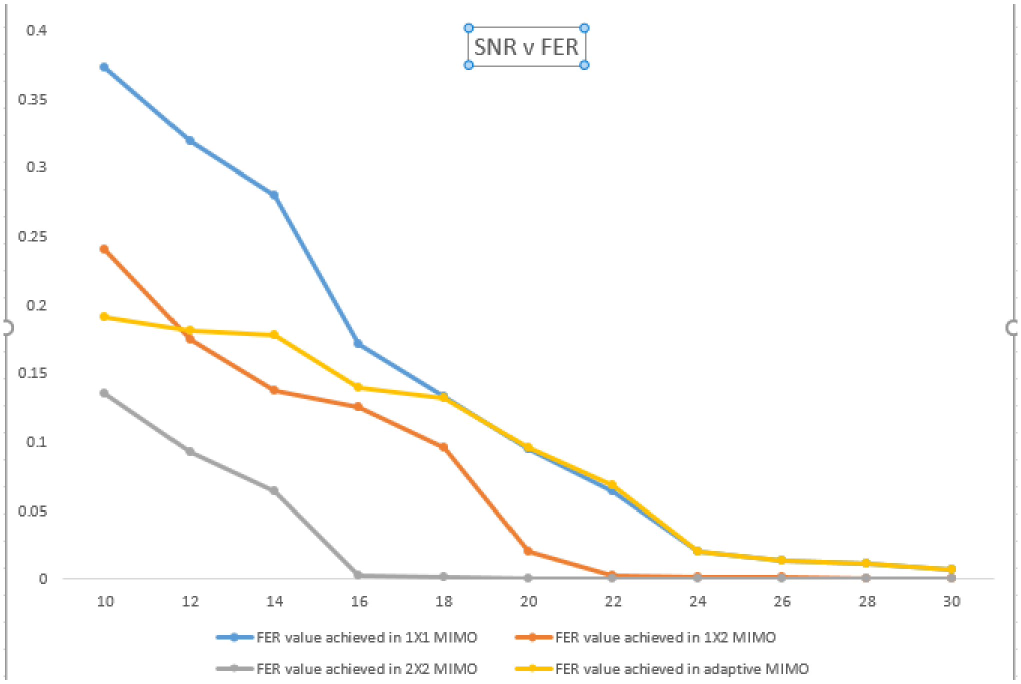

Figure 5. The effect of diversity on channel quality degradation in FER v SNR(Linear)

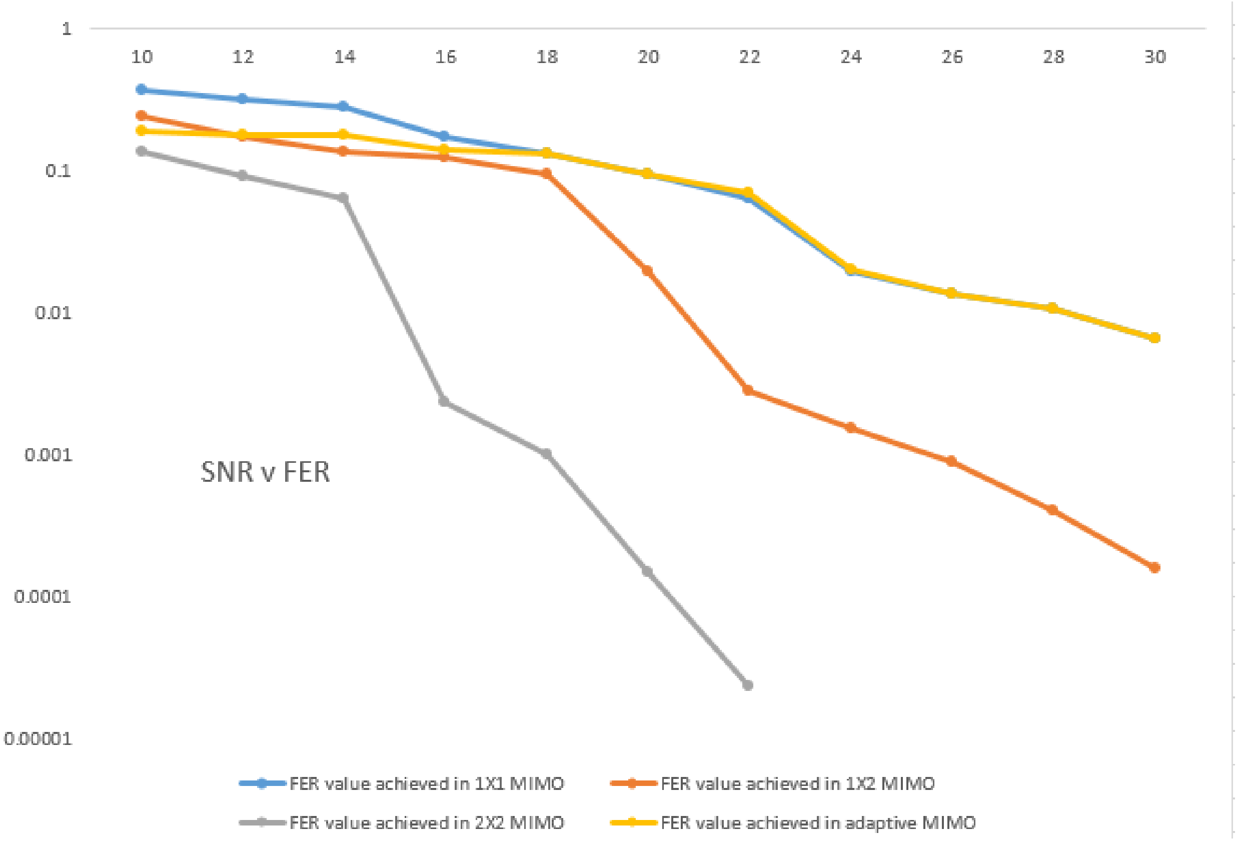

Figure 6. The effect of diversity on channel quality degradation in FER v SNR (Logscale)

6.1.1 Error Control Coding

The second strategy for increasing reliability is the application of error control coding. In Fig. 4, we have taken another degradation scenario of channel conditions, same as the diversity application. The channel condition degrades from 16 QAM to 8 QAM and 8 QAM to 4 QAM. If an error control mechanism is deployed, the system reliability degradation slows down significantly. We simulated the channel degradation for two different scenarios. Firstly, we did not deploy any error control coding. In the second Scenario, we used conventional coding and a clear improvement in channel reliability is observed. We used hard decision making scheme for Convolutional coding. We made this comparison in an AWGN channel, but the same observations can be made in Rayleigh and Ricean fading channels. As observed by separate simulation, the reliability of a system is affected by both incremental diversity and error control coding. Now, we can also show the

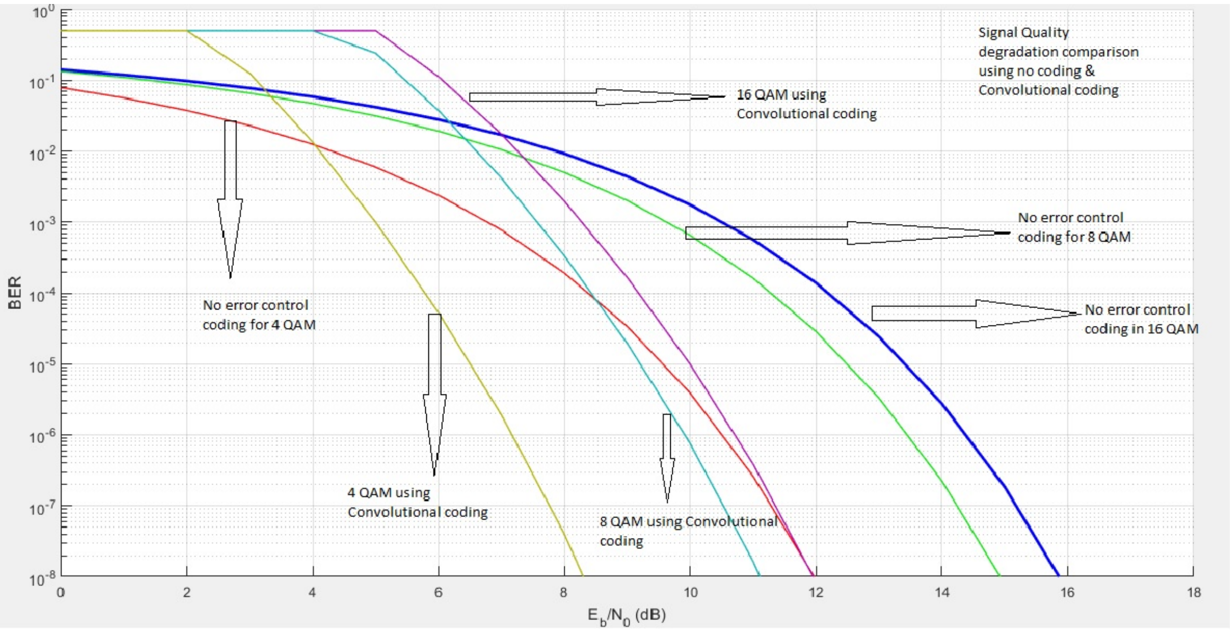

Figure 7. The effect of error control coding on channel quality degradation

effect of using diversity and coding, when they both are simultaneously applied. We used an existing Simulink MIMO model to show this. This Simulink model shows better reliability can be achieved, when we use more than one method of reliability control, cascaded together. In this model a user customizable MIMO up-to 2x2 is represented and OSTBC is used as an error control coding.

Table 4: BPSK v QPSK for 1x1 MIMO

SNR(in dB)	**FER value achieved in 1X1 MIMO - QPSK**	**FER value achieved in 1X1 MIMO - BPSK**
10	0.373134328	0.274725275
12	0.318471338	0.168350168
14	0.279329609	0.131578947
16	0.171232877	0.131578947
18	0.132978723	0.063371356
20	0.09487666	0.023331778

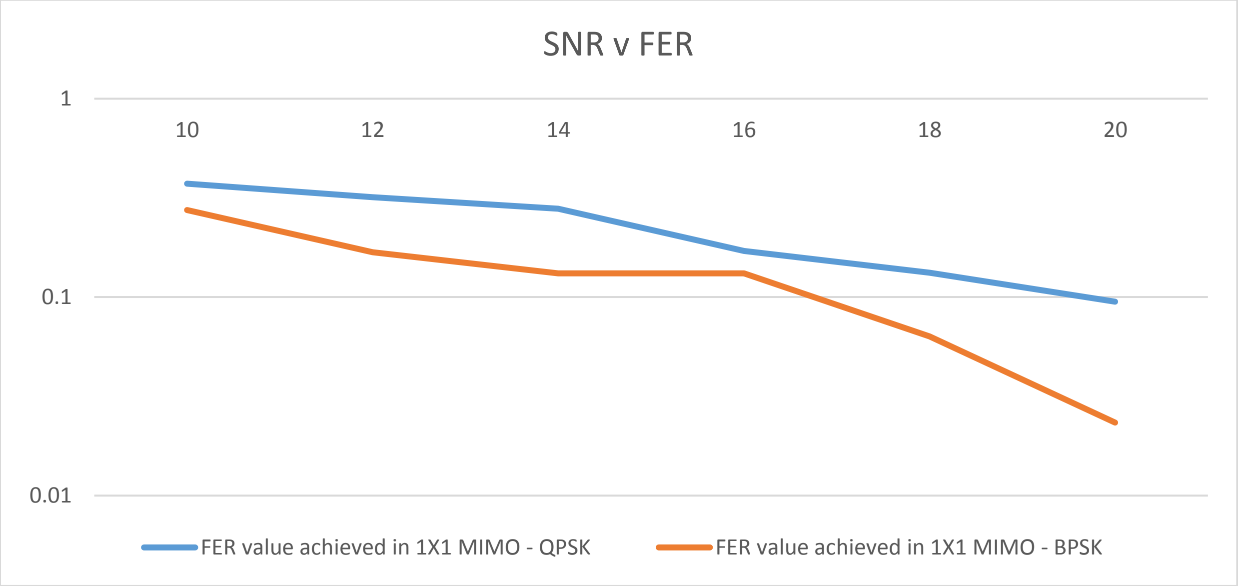

Figure 8. SNR v FER results for QPSK & BPSK for 1X1 MIMO

Table 5: BPSK v QPSK for 1x2 MIMO

SNR(in dB)	FER value achieved in 1X2 MIMO - QPSK	FER value achieved in 1X2 MIMO - BPSK
10	0.240384615	0.138504155
12	0.174825175	0.129198966
14	0.137362637	0.095238095
16	0.125628141	0.063291139
18	0.095419847	0.005007511
20	0.019447686	0.001738889

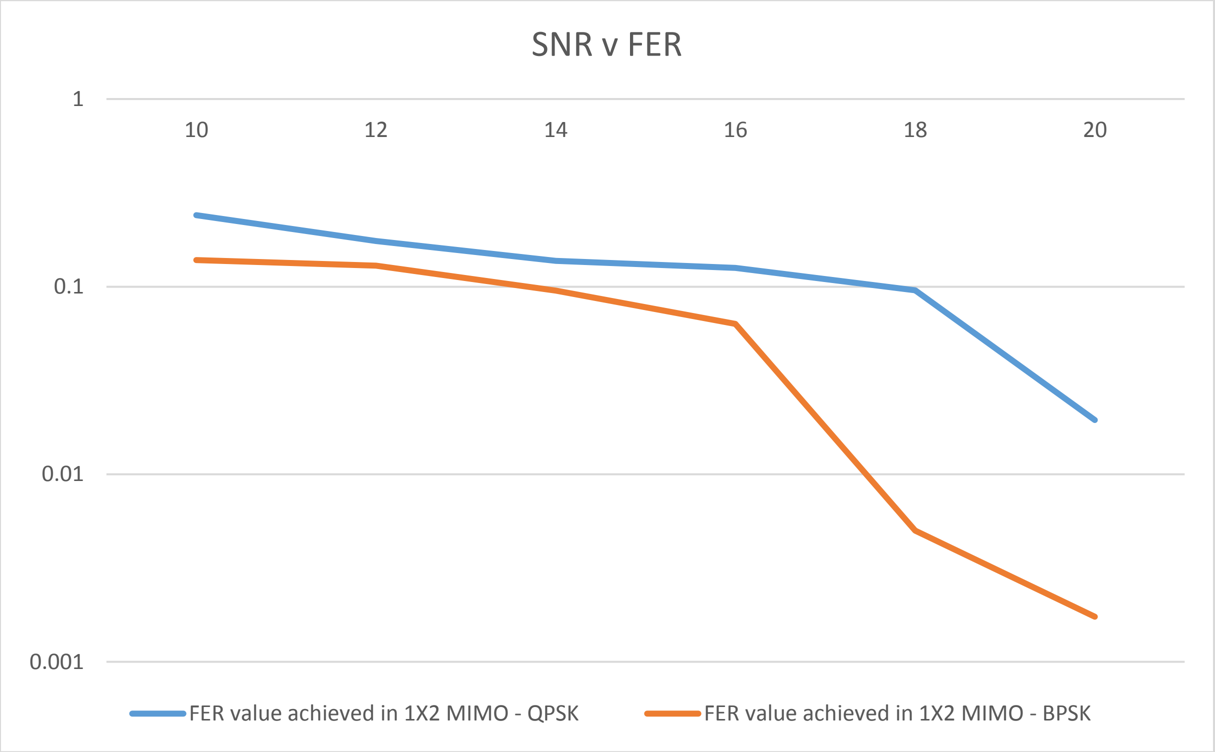

Figure 9. SNR v FER results for QPSK & BPSK for 1X2 MIMO

Table 6

BPSK v QPSK for 2x2 MIMO:

SNR(in dB)	**FER value achieved in 2X2 MIMO**	**FER value achieved in 2X2 MIMO**
10	0.135501355	0.066489362
12	0.092764378	0.002875877
14	0.063371356	9.95E-04
16	0.002350176	0.000160937

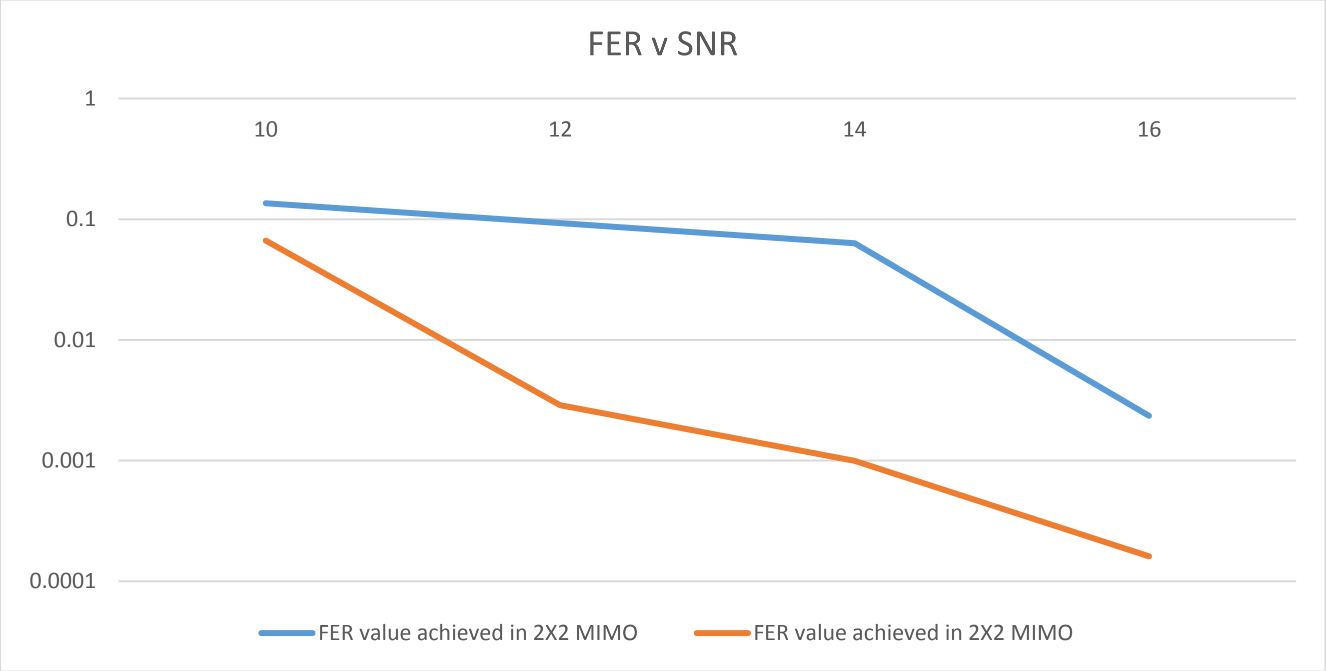

Figure 10 SNR v FER results for QPSK & BPSK for 2X2 MIMO

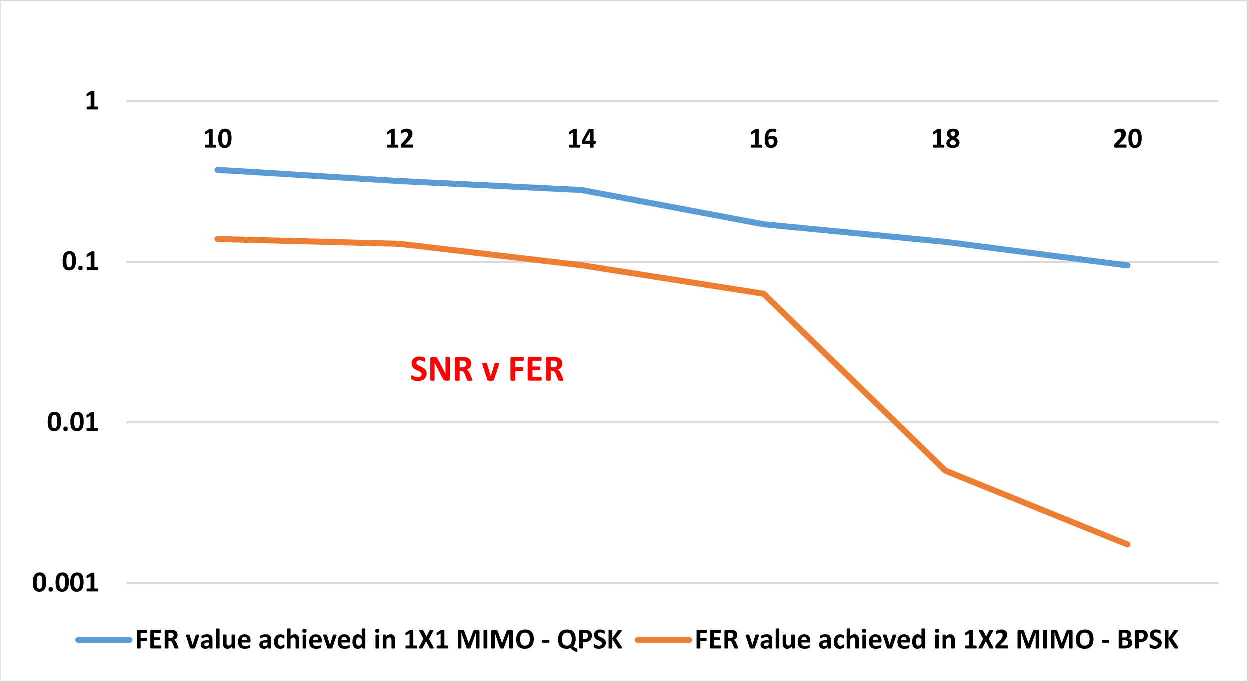

Figure 11. Comparison between 1X1 MIMO, QPSK v 1X2 MIMO, BPSK

CHAPTER 7

CONCLUSIONS AND FUTURE ASPECTS:

In this study, we described the factors which represent all the requirements to develop ultra-reliable, low latency communication networks. Based on the criteria we have suggested a theoretical model that combines the requirements of a future proof URLLC system. We used an existing simulation model to show here how combining two or more features like diversity, error control coding, or retransmission, Reliability of a system can be widely improved. If we can use feedback path, by fetching real time reliability statistics back to the system, further enhancement of reliability can also be achieved. The results of the simulation examples can be used further for better understanding of reliability improvement of a practical communication system. The theoretical model (Fig. 2) which is represented can be useful to development of a practical communication structure, which meets all the existing requirements of an ultra-reliable communication system.

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