SPARSE CODE MULTIPLE ACCESS WITH PRACTICAL SOFT-DEMAPPER FOR INTERNET-OF-THINGS APPLICATION

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DEDICATION

This thesis is dedicated to my wife, whose love and support kept me motivated in all the difficult times I faced during my thesis journey. It is also dedicated to my daughter, whose simple gestures of love and affection made me go further every time.

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ABSTRACT

Non-Orthogonal Multiple Access (NOMA) can address overloaded multi-user communications systems within some limits, in which Sparse Code Multiple Access (SCMA) is one of the favourable techniques. SCMA can provide reliability, spectrum efficiency, and higher overloading of resources. However, the current SCMA techniques are complex to be implemented in machine-to-machine (M2M) communication systems involving devices with limited capabilities. Moreover, the concerns about the practical implementation of SCMA needs to be addressed, mainly when the devices have limited processing power with acceptable performance degradation. The analysis of existing systems shows that the most processing-complex part of the SCMA architecture is the decoder, while the overloading of the system depends on the optimised multiplexing of user data on the resource elements. The main objective of this thesis is to propose a new SCMA decoder with a soft-demapping technique which can reduce computational complexity and improve the error rate performance of the system. For the practical implementation of the system, this thesis proposes optimised control parameters: Log-Likelihood Ratio (LLR) limiter ζ, and noise variance threshold ψ; to handle the stability of the system. Then, the proposed technique is analysed for higher overloading conditions with multi-device handling using an irregular factor matrix in terms of Bit Error Rate (BER) analysis. The higher overloading clarifies the performance of SCMA in dense massive IoT communication system. The results using MATLAB simulation show that for regular factor matrix, the proposed soft-demapper technique improves 33% in the execution time of the decoding operation compares to conventional SCMA. In terms of the number of iteration (T), the proposed technique shows a 63% reduction compares to conventional SCMA. For the practical implementation, it is found that the system has an optimised value of $\zeta = \pm 700$ for both regular and irregular matrices. Meanwhile, the optimised value for noise variance threshold is $\psi = 0.4$ and $\psi = 0.1$ for regular and irregular soft-demapper matrix, respectively. Comparing with the conventional SCMA, BER analysis of regular matrix demapper system under block Rayleigh fading channel shows an SNR gain of 2.5 dB at 10^{-3} BER, and under fast Rayleigh fading channel shows 1.1 dB SNR gain at 10^{-5} BER. Because of the difference in channels variation, different BER target is used for both channels. The system is also simulated with an irregular matrix and it achieved a higher overloading factor of 200% than regular matrix demapper with 150% overloading. It shows that the proposed SCMA decoder with soft-demapping technique is practical to be implemented even with the irregular matrix system with improved performance and additional capability to handle more users. The proposed technique allows improvements in SCMA adaptability in the Internet of Things (IoT) domain, which has the bottleneck of not having high-end computational hardware that requires higher multi-device access.

ABSTRAK

Capaian Berbilang Tidak Orthogon (NOMA) dapat mengatasi masalah multipengguna yang sarat di dalam sistem komunikasi dengan beberapa kekangan, di mana Kod Tatasusunan Capaian Berbilang (SCMA) adalah salah satu teknik pilihan yang terbaik. SCMA dapat menyediakan kebolehpercayaan, spektrum yang efisien, dan sarat dengan sumber yang tinggi. Walau bagaimanapun, teknik SCMA semasa adalah kompleks untuk diimplementasikan dalam sistem komunikasi mesin-ke-mesin (M2M) yang melibatkan kemampuan peranti yang terhad. Tambahan pula, implementasi SCMA yang praktikal perlu diberi perhatian, terutamanya apabila sesuatu peranti mempunyai kuasa pemprosesan yang terhad dengan prestasi yang menurun. Analisis pada sistem sedia ada menunjukkan bahagian yang paling kompleks di dalam seni bina SCMA adalah penyahkod, manakala sistem yang sarat bergantung kepada pemultipleks data pengguna yang optimum pada sumber elemen. Objektif utama tesis ini ialah untuk mencadangkan satu penyahkod SCMA dengan teknik penyahmeta lembut yang baru di mana ia dapat mengurangkan kompleksiti pengkomputeran dan meningkatkan kadar ralat prestasi sistem. Untuk implementasi sistem yang praktikal, tesis ini mencadangkan parameter terkawal yang optimum:penghad Log Nisbah Kebolehjadian (LLR) ζ dan ambang varians hingar ψ; untuk mengendalikan kestabilan sistem. Kemudian, teknik cadangan dianalisa melalui analisis Kadar Ralat Bit (BER) untuk situasi yang sarat dengan berbilang pengguna menggunakan kaedah faktor matriks tidak teratur. Keputusan kajian menggunakan simulasi MATLAB menunjukkan, bagi kaedah faktor matriks teratur, teknik cadangan iaitu penyahmeta lembut menambah baik masa pelaksanaan operasi penyahkod sebanyak 33% berbanding SCMA konvensional. Dari segi bilangan lelaran (T), teknik cadangan menunjukkan pengurangan sebanyak 63% berbanding SCMA konvensional. Untuk implementasi yang praktikal, telah didapati bahawa sistem ini mempunyai nilai optimum bagi penghad, $= \pm 700$ untuk kedua-dua teknik penyahmeta lembut matriks teratur dan tidak teratur. Sementara itu, nilai optimum bagi ambang varians hingar adalah masing-masing, $\psi = 0.4$ dan $\psi = 0.1$ bagi penyahmeta lembut matriks teratur dan tidak teratur. Untuk membandingkan dengan SCMA konvensional, analisis BER bagi matriks teratur pada saluran pudaran blok Rayleigh menunjukkan 2.5 dB gandaan SNR pada BER 10^{-3}, dan pada saluran pudaran laju Rayleigh menunujukkan 1.1 dB gandaan SNR pada BER 10^{-5}. Disebabkan perbezaan pada variasi saluran, sasaran BER adalah berbeza untuk kedua-dua saluran. Sistem ini juga disimulasi dengan matriks tidak teratur dan ia mencapai faktor sarat yang tinggi sebanyak 200% berbanding matriks teratur dengan 150% faktor sarat. Ini menunjukkan yang cadangan penyahkod SCMA dengan teknik penyahmeta lembut adalah praktikal untuk diimplementasi sekalipun menggunakan matriks tidak teratur dengan prestasi yang lebih baik dan mepunyai kebolehan menguruskan pengguna yang banyak. Teknik cadangan dapat menambah baik sistem SCMA untuk diadaptasi di dalam domain Internet Pelbagai Benda (IoT), yang tidak mempunyai perkakasan komputer atasan yang memerlukan banyak capaian berbilang peranti.

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LIST OF ABBREVIATIONS

1G - First-Generation Mobile System

2G - Second-Generation Mobile System

3G - Third-Generation Mobile System

3GPP - 3rd Generation Partner Project

4G - Fourth-Generation Mobile System

5G - Fifth-Generation Mobile System

AWGN - Additive White Gaussian Noise

BER - Bit Error Rate

CDMA - Code Division Multiple Access

CB - Codebook

CM - Constellation Matrix

CP - Cyclic Prefix

EXIT - Extrinsic Information Transfer-Function

FDMA - Frequency Division Multiple Access

GSM - Global System For Mobile Communication

GAM - Golden Angle Modulation

IoT - Internet of Things

IMUDD - Iterative Multi-User Detection/Decoder

KPI - Key Performance Indicators

LDPC - Low-Density-Parity-Check

LDS - Low-Density Spreading

LDS-CDMA - Low-Density Spreading Code Division Multiple Access

LDS-OFDM - LDS Aided Orthogonal Frequency Division Multiplexing

LIM - Limiter

LOG-MPA - Logarithmic-Domain Message Passing Algorithm

LTE - Long Term Evolution

LDM - Layered Division Multiplexing

LPMA	-	Lattice Partition Multiple Access
MC	-	Multidimensional Constellation
MED	-	Minimum Euclidean Distance
MUST	-	Multi-User Superposition Transmission
MUSA	-	Multi-User Shared Access
MIMO	-	Multiple Inputs Multiple Outputs
MPA	-	Message Passing Algorithm
MUSA	-	Multi-User Shared Access
NOMA	-	Non-Orthogonal Multiple Access
OMA	-	Orthogonal Multiple Access
OFDMA	-	Orthogonal Frequency Division Multiple Access
PAM	-	Pulse Amplitude Modulation
PDMA	-	Pattern Division Multiple Access
QAM	-	Quadrature Amplitude Modulation
SCMA	-	Sparse Code Multiple Access
SIC	-	Successive Interference Cancellation
SNR	-	Signal-To-Noise Ratio
SEFDM	-	Spectrally Efficient Frequency Division Multiplexing
TDMA	-	Time-Division Multiple Access
URLLC	-	Ultra-Reliable Low Latency Communication

LIST OF SYMBOLS

W - Codewrods

N_cu - Number of Channels to transmit one codeword

V - Total number of users

S - Spreading matrix

X - Multi-dimentional constellation

K - Number of resources

d_v - Number of users multiplexe on one resource element

d_f - Number of concurrent resources to tranmit user data

σ - Standard deviation

σ^2 - Variance

Π - Interleaver

Π^{-1} - Deinterleaver

M^{-1} - Demapper

T - Number of Decoder Iterations

Q_b - Minimum bit error rate

E_b/N_o - Signal to noise per bit

ζ - Limiter

ψ - Threshold

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

Wireless communication has passed through a broad span of research and development, which has shaped it into the modern advanced structure [1]. It has gone through four significant generations, incorporating advancements in different parameters and improving the system's capability [2]. Over the generations of wireless communication, there have been improvements in resource utilisation, where resources are either time or frequency blocks. Each generation has incorporated new ways of passing the maximum amount of user data through the limited bandwidth with the best possible benchmarks [3]. Different multiplexing techniques have been proposed in each 1-4 Generation (1G, 2G, 3G and 4G) mobile system, and each generation is unique in its use of a multiple access technique. Specifically, 1G wireless communication used Frequency Division Multiple Access (FDMA) in handling resource utilisation, while 2G incorporated Time-Division Multiple Access (TDMA). 3G communication was mainly based on Code Division Multiple Access (CDMA); in contrast, 4G used an advanced FDMA version called orthogonal FDMA (OFDMA) [4]. The techniques incorporated in 1G-4G systems use the orthogonal allocation of resources for users. The orthogonal multiple access (OMA) idea exists in dividing single narrow-band frequency resource among different users orthogonally. The technique allows the mitigation of interference among various users and improving communication reliability.

The exponentially growing Internet of Things (IoT) has created many challenges for wireless communication systems. The main drawbacks are mobile wireless communication systems that were not designed for machine-to-machine (M2M) communication. The difference is that M2M needs high multi-device access because of the very high density of devices on a small spatial scale. The challenge mainly exists when the requirements grow even further since, according to International Data Corporation (IDC) predictions, the number of IoT devices in operation by 2025 will be 41.6 billion [5]. Further, these devices need communication systems with low computational overhead and hardware optimised system designs. The M2M communication in IoT is mostly through short-range communication protocols like Bluetooth, Wi-Fi and Zigbee; however, long-range communication is carried using mobile communication systems. M2M IoT communication's good point is its low bandwidth, leading to narrow-band communication with highly optimised architecture to be ideal for such transmissions [6, 7].

The existing division of time/frequency resources among users has limited spectrum utilisation and connectivity capability. Non-orthogonal multiple access (NOMA) techniques exist in modern telecommunication systems to improve spectrum efficiency and achieve better resource utilisation [8]. It assigns resources to users on a sharing basis rather than division. The sharing allows improved utilisation of a single resource, thereby improving spectral efficiency [9]. The sharing is necessary for the modern wireless and telecommunication systems because of mobile internet, and the IoT [10].

Like the OMA, NOMA also has several techniques under its umbrella. These techniques or methods are categorised based on the type of sharing mechanism used, mainly classified into power domain, code-domain, and multiple domain NOMA [11]. The power domain NOMA is a single carrier technique multiplexing various users in the same resource block by varying their power levels based on individual channel conditions. This multiplexed data is separated at the receiver through successive interference cancellation (SIC) technique, in which user data is extracted. Power domain NOMA has a significant spectral advantage over the OMA techniques. Additionally, due to SIC based receiver having a more straightforward decoding mechanism, the power domain NOMA has a simpler receiver architecture. Based on this, the power domain NOMA is suitable for downlink communication [12].

Unlike power domain NOMA, code domain NOMA includes multi-carrier techniques and can accommodate multiple users within the same resource block. Like the power domain, in code domain NOMA, various users are differentiated based on codes. The main techniques preferred for reliability under code-domain NOMA are low-density spreading (LDS) and sparse code multiple access (SCMA). In LDS, data of different users are distributed sparsely in assigned resource blocks. Therefore, each user is assigned a subset of resource blocks, and this subset is not common among the different users. The LDS data assignment is based on the repetition of constellation points, based on which data is spread in the assigned resource blocks. Due to the sparse nature of data being distributed in resource blocks, it is easier to separate user data at the receiver end. The complexity of the receiver is significantly reduced. The standard message passing algorithm (MPA) is used to detect multi-user at the receiver end [13]. The other code domain scheme, SCMA, is an advanced version of LDS and works on the same principle of sharing resources among multi-users by sparsely spreading data in the assigned resource blocks. The difference between the two exists in the data encoding. SCMA uses multidimensional constellations to map the input bits into codewords instead of repeating constellation points over all the assigned resource blocks. In SCMA, different characters are used for each resource block, making it more robust and complex [14].

Multiple-domain NOMA incorporates power, code, and spatial domain in multiplexing user data [15]. To achieve this, the prominent techniques in this category are pattern division multiple access (PDMA) and lattice partition multiple access (LPMA). PDMA sparsely spread user data on the assigned resource blocks like SCMA. Still, the number of allocated resources is not fixed, and a variable number of resources are available for different users [16]. The differentiating domain is also not constant, and data can be multiplexed in either power, code, or spatial domain. Additional areas for different data clusters require SIC and Maximum a posteriori (MAP) decoder in conjugation for multi-user separation. In contrast, LPMA uses code and power domains combined for user data multiplexing. Based on the channel conditions, a multilevel lattice code allocates different codes to different users. Comparable to power domain NOMA, SIC is used at the receiver end for user recognition [17].

There has been extensive study on the comparison of different NOMA techniques considering various aspects. In the literature, [15], the superiority of code and multiple domain NOMA techniques is presented because, unlike power domain NOMA, these are less affected by channel conditions. Also, the MPA detector used in code and multiple domain NOMA has a near-optimal detection than the SIC detector. However, the optimised nature of MPA is due to the sophisticated algorithm in its operation, thereby increasing receiver complexity. A comparison between the power and code domain NOMA [16] also concludes that although code domain SCMA has a highly complex receiver architecture than the power domain NOMA still its performance is much better. Research also shows that within multi and code domain SCMA, SCMA has a much better performance than PDMA because of the multidimensional constellation design [18]. From the performance point of view, SCMA is found to have higher robustness and can work better under high resource utilisation [19]. SCMA is also a better option for uplink communication [20] and has a low latency communication suitable for modern systems [21]. The technique has already been studied for M2M transmission in the uplink, providing high multiplexing capability [20].

SCMA can be incorporated in the IoT M2M communication and has already been used in various scenarios. However, to incorporate SCMA into different application scenarios, specific requirements need to be fulfilled. Like in M2M communication, the SCMA architecture needs customisation and must pass compatibility challenges to be integrated. Regarding IoT, these challenges are related to hardware optimisation and the enhancement of mass communication capabilities. The subsequent section discuss the specific problems under these broad domains and what study objectives are set to mitigate these challenges.

1.2 Problem Statement

Current SCMA technique is complex to be implemented in machine-to-machine (M2M) communication system involving devices with limited capabilities. Analysis of existing systems shows that the most processing-complex part of the SCMA architecture is the decoder. SCMA system require decoder which can reduce computational complexity and improve the error rate performance of the system. Many research approaches are using different techniques for decoder enhancement. Maximum a posteriori (MAP) based MPA and log-MPA decoders are frequently used in SCMA architecture considering their low complexity, but, it induces performance limitations in the system implementation [22]. Maximum likelihood (ML) is considered for multi-user detection. However, due to high computational complexity, its implementation is quite limited [23]. Modern machine learning technique has also been presented to be effective [24]. However, such a technique is problematic when the number of users/devices increases. Considering all the cases, the commonly used iterative message-passing algorithm leads to a higher number of iterations for convergence and causing processing and delay as an overhead. Soft-demapping based decoding serves as an alternate for achieving higher convergence efficiency. It has been studied as an optimised decoder in [25], where the decision threshold algorithm is used for demapping the data with low computational complexity and with high throughput. Alhamdi in [26] also used Optimal Soft Demapper for 5G new radio (NR) Wireless Communication Systems proposing thresholds for practical applications. Considering the requirement of M2M communication in IoT, soft demapper is preferred as a computationally better and fast converging decoder. However, incorporating a soft demapper based decoder and its practical implementation for SCMA architecture needs to be researched.

Considering the limited resource in M2M communication of IoT, the practical implementation of SCMA needs to be addressed with acceptable performance degradation. SCMA system needs to have parameters and thresholds for operating the system in a controlled manner considering data path complexities in SCMA.

SCMA system is also required to multiplex the data in a more efficient way without effecting the BER performance. For improving multi-device communication, various research approaches exist. Full-duplex communication is presented in [27] for ultra-reliable and low latency communications (URLLC) in the IoT to enhance the multi-user capability by using the short packet transmission of IoT devices in both uplink and downlink communication. Frequency hopping based SCMA has also been studied for handling the massive connectivity improvements in IoT communication [28], but the receiver complexity due to hopping has not been considered in the study. The mapping matrix's nature is studied in [29], which proposes irregular degree distribution in the mapping matrix for higher connectivity. Comparing a regular and irregular matrix has shown that with better system design, the SCMA system's performance can be improved using an irregular mapping matrix. Yu et al. in [30] showed that irregular SCMA has a better bit error rate (BER) performance, especially at higher SNRs. However, the challenges concerning decoder complexity and decoding performance are not considered. So, concerning IoT, there is a need to have a study on the trade-off between decoding complexity and performance considering high multi-device communication.

1.3 Research Objectives (RO)

The research aims to design an SCMA system for massive IoT M2M communication through encoder and decoder optimisation. Concerning that, the research objectives are,

- to propose a new SCMA decoder with soft demapping technique having reduced computational complexity,
- to optimise the soft demapper parameters for practical implementation of SCMA for IoT application,
- to evaluate the performance of the proposed design based on complexity and BER analysis under high overloading machine type communication (MTC) scenario.

1.4 Research Scope

The research deals with the solution to reduce the complexity of the iterative MPA decoders and improve the decoding convergence efficiency. The designed/proposed solution is to be tested for practical implementation using various parameters, and the challenges in its execution are thereby addressed. Lastly, the optimised architecture is tested for higher overloading conditions suitable for dense M2M communication, and results will be analysed for improvements.

The designed system provide a computationally less intensive and fast converging decoder that allow the SCMA system to be incorporated into devices with less processing capabilities. The proposed system help to handle the IoT M2M communication scenario in an optimised way. Multiple IoT devices are considered using multiple channels for uplink data communication to test the proposed system. The higher overloading capability of the SCMA system is simulated using an optimised factor graph matrix for encoding multi-user data on the resource blocks. An optimised matrix allow more users to share the same number of resource blocks without compromising communication reliability.

Evaluation of data mapping and demapping is simulated using the simulation environment in *Matrix Laboratory (MATLAB)*. The study is limited to handling six to eight users on a single frequency resource. The BER is considered to identify the factor graph's optimal design and demapper capabilities. Performance evaluation of the system is performed against existing systems referenced in articles/patents.

The study has the limitation of lacking real-time system testing with actual user data. Since the task requires real telecommunication hardware for the base station and corresponding user equipment, the research help get the system's true performance. However, the current study is limited to the simulation domain analysing the offline results of the system.

1.5 Research Contribution

This study undertake the multi-device communication optimisation problem in the IoT domain, considering the use of massive IoT devices. The main contributions of this research are as follows:

- To propose and implement a fast converging and computationally better SCMA decoder utilising soft-demapping technique to improve the system's adaptability in IoT devices.
- Evaluating the overloading capability of the SCMA system by incorporating optimal decoder with the high order factor graph for MTC/M2M application and overloading scenario.

1.6 Thesis Organization

The document consists of five chapters: introduction, literature review, methodology, results, and conclusion. The introduction described the research background and related issues, objectives, problem statement, and work scope.

The second chapter covers the literature review providing an overview and a critical review of various system designs and system analysis of NOMA techniques. It initially explains the OMA techniques and their limitation from the literature; then, NOMA is described with emphasis on research presenting its effectiveness compared to OMA systems. SCMA literature and its implementation in uplink and downlink systems are explained in the next part. It also encapsulates the advancements carried out in developing methods for IoT networks using the SCMA technique.

The third chapter presents the research methodology and the proposed SCMA system, which covers different design aspects. The flow chart based on the research objectives is presented. The practical soft demapper system design is developed, and the mathematical model is presented. The system performance considered in this thesis is explained in this chapter.

In chapter four, the results of the proposed system for various channel models is presented. Based on the objectives, the BER and complexity analysis are carried out for overloading and decoder optimisation. Initially, the parameter optimisation for various control and tuning parameters is performed. The parameters are used in the complexity analysis of the decoding sequence to test the algorithm convergence. These same parameters are then used in the BER analysis of overloaded and soft demapper based SCMA. Testing under different scenarios ensures the system's durability and presents the actual picture of the system response.

The last chapter presents the concluding remarks emphasising the linkage between the system results and the real-world application. The chapter also handles future work, which can further benefit the problem statement.

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Appendix A Forward Error Correction Coding

A.1 Repetition Coding

In the repetition codes, the typical transmission faults can be rectified at the receiver without re transmission using the error correction coding technique. Through the repetition coding error correction coding approach, common transmission errors can be corrected at the receiver without re transmission. The redundancy in the data bits ensures the opportunity to repair errors. In the case of n number of repetitive data bits, the number of error bits that can be corrected is given by $(n - 1)/2$.

For instance, considering the most basic repeating codes, When the sent bit is 1, we can transmit it five times, resulting in bit sequence 11111 being sent out. The majority rule is used by the decoder, which means that the most common bit in the received sequence is used to decide. As a result, if the decoder receives bits 01111 due to a transmission fault, the decoder can claim that the information bit is one and repair the error. The transmission rate, commonly abbreviated as R, is the ratio of the number of information bits to coded bits. The transmission rate of the repetition code in the example above is 1/5. The corresponding code is represented by a generator matrix G and a parity–check matrix H defined as follows

$$G = (1 \ \ 1 \ \ 1 \ \ 1 \ \ 1) \tag{A.1}$$

and

$$\mathbf{H} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} . \tag{A.2}$$

The smaller R, the more redundancies are incorporated, and the more reliable the transmission becomes; nevertheless, a smaller R requires more communication bandwidth because the transmitter must send out more coded bits in the same amount of time. A balance between reliability and resource use is required.

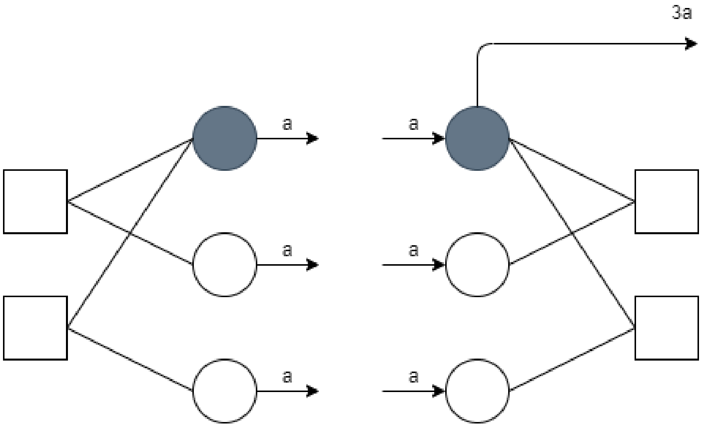

Figure A.1: Repetition decoding sequence

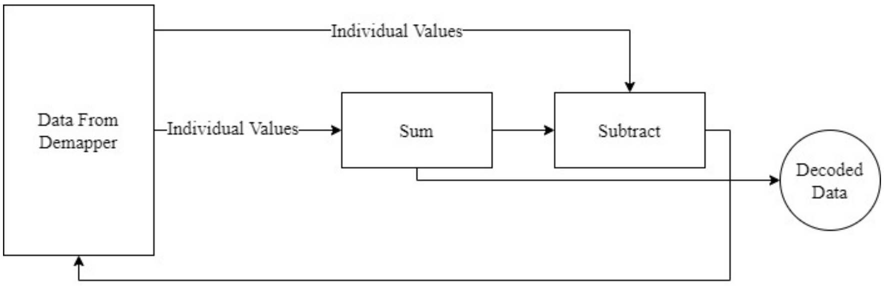

Figure A.2: Receiver operations for Repetition Coding

Practically, the EC decoder has two outputs, one it generates the priori data for the decoder by decoding the individual redundant data elements through subtracting their value from the sum of all the repetitive parts. Secondly, it outputs the transmitted user data by summation of all the repetitive data elements. This addition omits errors less then $(n-1)/2$ from data and generates a correct value for transmitted user/device data.Considering 'a' to be the user data, the sequence of operation in the repetition decoding and its main blocks are shown in Figure A.1 and Figure A.2 respectively.

Appendix B Interleaving

There are three main types of interleaving techniques presented in the literature. Namely block interleaver, convolutional interleaver, and random interleaver. A block interleaver rearranges the input matrix in a way that the data in the output matrix is written row wise and read out column wise [129] as shown in Figure B.1.

Like interleaver, the block deinterleaver reads the matrix with data elements column by column and then sends the matrix contents in the form of row by row to the output, as shown in Figure B.2.

Block interleaver is suitable for the case hen error patterns are limited to a single row. If error is spread in several consecutive rows like in the case of concatenated errors which are spread over a number of rows, then the interleaving method needs to be altered in a way that column of interleaving matrix is read out in a specific format to spread as many error patterns as possible [130].

Convolutional interleaver consist of commutator at the input and output nodes along with a bank of shift registers. Input data in the form of blocks is inserted cyclically into the shift registers by the commutator. The placement generates a delay in the transmission by the shift registers. The output commutator in the same way samples the data cyclically from the shift registers. At the deinterleaver end the inverse operation is performed i.e. each bit in the block is delayed by the same shift registers, thereby generating the original data [131].

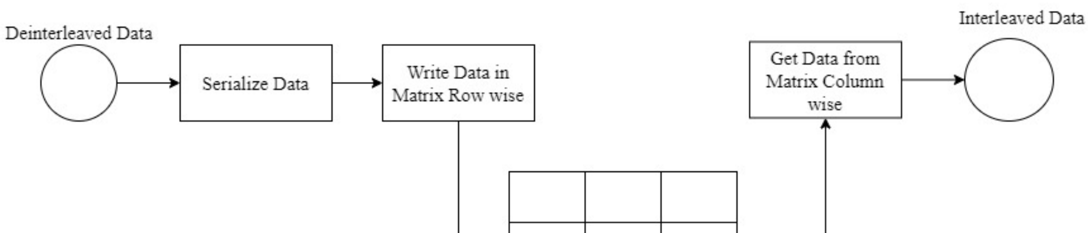

Figure B.1: Block interleaver sequence

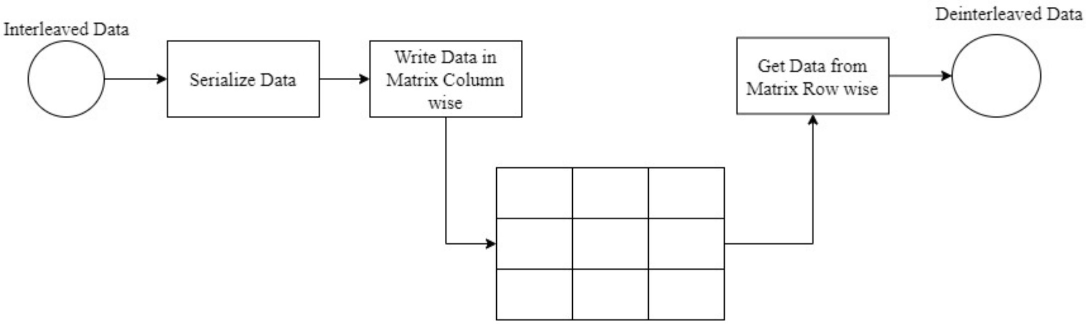

Figure B.2: Block de-interleaver

In the case of random interleaver a block of bits is taken as input which is read out randomly. The interleaver vector $\Pi(i)$, where $i \in 1, 2 \ldots N$ for N steps of interleaver can be generated by choosing randomly an integer i from the set $A = 1, 2, \ldots, N$, according to a uniform distribution between 1 and N [132].

Appendix C Fading Channel Types

The appendix presents explanation on different fading channels existing,

1. Flat Fading Channel: Flat fading is the name given to the case when the channel coherence bandwidth is larger than the signal bandwidth and hence all frequencies of the transmitted signal experience the same channel condition; i.e., over the signal bandwidth, the channel frequency response is essentially flat; and hence the name Flat Fading. In the time domain, this corresponds to having an expected smaller than the signal symbol period.
2. Block Rayleigh Fading Channel: The block-fading channel model assumes that the channel coefficients remain constant for a block of T consecutive symbols and change to an independent realization in the next block [7]. The parameter T can be thought of as the channel's coherence time, or more generally, the number of time-frequency slots over which the channel stays constant.A codeword of length n = LT spans L independent channel realizations
3. Fast Rayleigh Fading Channel: In a fast Rayleigh fading channel, the rate of change of the channel is higher than the signal symbol period and hence the channel changes over one period. In other words, the channel coherence time, Tc, is smaller than the symbol period.
4. Frequency Selective Fading Channel: if the channel bandwidth is narrower than the signal bandwidth, different frequency bands of the signal are affected differently. The time domain analogue is that the channel is larger than the signal symbol period.
5. Slow Fading Channel: In a slow fading channel, the channel coherence time is larger than the symbol period and hence the channel remains approximately static over a symbol or multiple symbols. Slow fading is usually expected with low Doppler spread values; i.e. with slower moving obstacles and receiver/transmitter.

LIST OF PUBLICATIONS

Indexed Journal

1. **Hussain, S. A.**, Ahmad, N., Shayea, I., Kaidi, H. M., Abdul, L., Latiff, N. M., & Sam, S. M. (2021). A review of codebook design methods for sparse code multiple access. Indonesian Journal of Electrical Engineering and Computer Science, 22(2), 319-327. (Indexed by SCOPUS)
2. Iqbal, M. S., Rahim, Z. B. A., **Hussain, S. A**, Ahmad, N., Kaidi, H. M., Ahmad, R., & Dziyauddin, R. A. (2020). Mobile Communication (2G, 3G &4G) and Future Interest of 5G in Pakistan: A Review. Indonesian Journal of Electrical Engineering and Computer Science, 15(3). (Indexed by SCOPUS)