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**PERFORMANCE INVESTIGATIONS OF SCMA
SYSTEMS**

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TOLGA KAĞAN TÜFEKÇİ

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To my family

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ABSTRACT

In order to meet the ever-increasing demands of high data rates, low latency, as well as higher spectral efficiency, and high throughput, newer communications techniques have been developed. Sparse Code Multiple Access (SCMA) is one of the promising techniques. SCMA is a Non-Orthogonal Access (NOMA) scheme. Using SCMA, different users can be allocated on the same frequency resources, increasing spectral efficiency. Each user is assigned a sparse multi-dimensional complex valued codebook; due to this, SCMA systems are dependent on the quality of the codebook. In this thesis, the performance of SCMA systems is examined under different scenarios; these are, 1) The effect of Fast-Fading Rayleigh Channels for SCMA systems are investigated and a method called High Rate MPA (HR-MPA) is proposed to reduce the adverse effects of the fast-fading channels. 2) Channel Estimations using Non-Orthogonal and Orthogonal Pilot Sequences with Least-Squares Estimations 3) Effect of Intersymbol Interference (ISI) on SCMA systems and generation and use of PN Sequences in the presence of ISI. 4) Effect of different codebooks on the performance of SCMA systems in the literature and a Genetic Algorithm-based codebook design method.

Keywords: SCMA, Sparse Code Multiple Access, 5G, NOMA

SCMA SİSTEMLERİNİN PERFORMANS İNCELEMELERİ

ÖZET

Sürekli yükselen; veri hızı, düşük gecikme, spektral verimlilik ve veri hacmi ihtiyaçlarını karşılayabilmek adına yeni haberleşme yöntemleri geliştirilmektedir. Seyrek Kodlu Çoklu Erişim (Sparse Code Multiple Access - SCMA) bu tekniklerin arasında yer almaktadır. SCMA, dikgen olmayan çoklu erişim (Non-orthogonal Multiple Access - NOMA) yöntemidir. SCMA ile farklı kullanıcılar aynı frekans kaynaklarına atanmasından dolayı spektral verimlilik arttırılır. Her kullanıcıya; seyrek, çok boyutlu ve kompleks değerli kod kitapları atanır, bu sebeple SCMA sistemlerinin performansı da kod kitaplarının kalitesine bağlıdır. Bu tezde; SCMA sistemlerinin farklı senaryolar altındaki performansları incelenmiştir bunlar, 1) Hızlı Sönümlenen Rayleigh Kanallarının etkisi incelenmiş ve bu kanal tipinin SCMA performansındaki negatif etkileri azaltabilmek adına Hızlı Mesaj İletim Algoritması (High-Rate MPA) önerilmiştir. 2) Dikgen ve dikgen olmayan pilot sekansları ve bu sekanslardan yola çıkarak En Küçük Kareler Kestirimi (Least Squares Estimation) yapılmıştır. 3) Simgelerarası Karışmanın (Intersymbol Interference - ISI), SCMA sistemleri üzerindeki etkisi ve PN Sekanslarının üretimi ve kullanımı incelenmiştir. 4) Literatürde bulunan farklı kod kitaplarının SCMA sistemlerindeki performansı incelenmiş ve ayrıca Genetik Algoritma tabanlı bir kod kitabının tasarımı ve yine etkisi incelenmiştir.

Anahtar Sözcükler: SCMA, Seyrek Kodlu Çoklu Erişim, 5G, NOMA

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1. INTRODUCTION

Due to the astonishing increase in the computational capabilities and memory-wise powers of electronics, data-heavy technologies such as Artificial Intelligence, the Internet of Things(IoT), and Big Data have been climbing the ranks of popularity in terms of overall usage and have their fields of applications expanded. This, combined with the increased number of devices connected to the internet, puts a tremendous burden on the current wireless communication systems. To meet the requirements envisioned for 5G, such as; bit rate in the Gbps band, extremely low latency, and very high coverage [1], with the problems mentioned above, traditional wireless communication technologies must undergo drastic changes. From First Generation (1G) to Fourth Generation (4G), each generation, approximately ten years apart, had the motivation to address the current problems with wireless communications and solve the flaws of their respective predecessors.

An overview of each generation can be summarized as [2], [3]; 1G is based on analog voice communications and can support up to 2.4kbps data rate and was developed in the 1980s. Still, the drawbacks of this generation were below-subpar security measures, low voice quality, and inefficient use of capacity. Approximately after ten years in the early 1990s, 2G was presented and mainly used for digital voice communications and could support up to 64kbps. It also had support for Short Message Service (SMS). Also, it deployed Time Division Multiple Access (TDMA), where users are allocated to the whole frequency resource within a small fraction of time. Code Domain Multiple Access (CDMA), where each user is assigned some code to transmit data, data rates still need to be higher, and it needed help to satisfy the demands. At the beginning of the 21st century, 3G was introduced and could support up to 2Mbps. In addition to communication over the voice in 1G and 2G, it could support faxing, paging, browsing on the web, video conferences,

and videos; however, in terms of energy consumption, it was inferior to 2G and was more expensive in terms of network architecture [4], following 3G, at 2010 4G was presented with the support of 100Mbps data rate with goals such as high security and capacity, multimedia over the internet and reliable internet communications using OFDM and CDMA.

Long-Term Evolution (LTE) stands between 4G and 5G, even though it provides very low latency and high data rates. However, Machine-to-Machine (M2M) and IoT technologies need an infrastructure that supports thousands of devices connected to a single cell. Still, LTE, by nature, can only support up to 600 RRC-connected users in a cell [5]. With all the mentioned drawbacks and disadvantages of the previous technologies, 5G aims to provide even better connectivity, much lower latency, higher data rates, more efficient use of radio spectrum, and lower energy consumption [6], by extending the capabilities of previous technologies 5G can natively support new use cases these can be summarized as [7]:

- Enhanced Mobile Broadband (eMBB)
- Massive Machine Type Communications (mMTC)
- Ultra Reliable Low Latency Communication (uRLLC)

The previous access technologies are Orthogonal Multiple Access (OMA) schemes. OMA schemes work by allocating different users to different resources, whether in code, time, or frequency; by doing so, they aim to reduce inter-user interference. Excessive growth of end devices makes it harder to allocate users in different resources and thus adversely affects spectral efficiency. 5G systems are expected to adopt Non-Orthogonal Multiple Access (NOMA) schemes to address this issue. In NOMA, it is possible for different users to be allocated to the same resource, either in code or power domain. The advantages of NOMA over OMA are; better spectral efficiency, lower latency, massive connectivity, and lower signaling cost [8].

NOMA can be divided into two sub-categories: Code Domain NOMA (CD-NOMA) and Power Domain NOMA (PD-NOMA). In CD-NOMA, like CDMA, user signals

are multiplexed over the same time and frequency resources by their respective code. In PD-NOMA, each user has their own power levels determined by their channel conditions. Sparse Code Multiple Access (SCMA) falls into the CD-NOMA category, where users have their own sparse codebooks. Because of that, SCMA achieves better than other NOMA methods due to its constellation coding gain [9], [10].

1.1 Literature on SCMA

SCMA was first introduced in 2014 [11] as an alternative to Low-Density Signature (LDS) proposed by Hoshyar et al. Since then, it has been extensively researched in many ways to assess its performance in different ways, such as optimal codebook and low complexity receiver design and application of SCMA systems on large scales. These studies' performances are mostly limited to the computer simulation results. In [12], authors compared PD-NOMA and SCMA in terms of their sum rates and showed that while SCMA has higher complexity, it is substantially better than PD-NOMA in terms of sum rate. Another study showed that uplink SCMA systems can support up to 2.8 times more users than OFDMA [13]. Nikopur et al. [14] proposed a resource allocation method for downlink SCMA systems. Studies in [15], [16], [17] have proposed different receiver designs for SCMA systems. Kim et. al [18], proposed a deep-learning-based decoder for SCMA systems and have shown improvements to the MPA. There are also numerous studies in the literature on the codebook design for SCMA systems. Huang et al. [19], proposed a codebook design for downlink SCMA systems in AWGN channels by maximizing the minimum Euclidean distance of superimposed codewords. Yu et al. proposed a Star-QAM signaling-based codebook design. Lei et al. [20], designed a codebook for uplink Ricean channels. [21], [22] proposed a genetic algorithm-based codebook design for SCMA systems, and [23] proposed differential evolution-based codebook design for both AWGN and Rayleigh channels.

1.2 Contributions and Summary

This thesis investigates the performance of SCMA under different systematic conditions. This investigation starts by first examining the performance deficit of SCMA systems under both correlated and uncorrelated fast-fading channel conditions and a possible solution to decrease the adversity coming from fast-fading, then use of non-orthogonal pilots for channel estimation and Genetic Algorithm based non-orthogonal pilot design method is presented and compared with non-orthogonal pilots for SCMA in the literature. Furthermore, the effect of Inter symbol Interference and PN Sequences are investigated under ISI conditions. Lastly, a channel-independent Genetic Algorithm-based codebook design for SCMA systems is investigated.

2. SPARSE CODE MULTIPLE ACCESS

This chapter discusses the generic SCMA system model and symbol detection.

2.1 SCMA System Model

SCMA was first introduced in [11] as an alternative to Low-Density Signature (LDS) proposed by Hoshyar et al. Different from LDS, SCMA combines QAM mapper and CDMA spreader to make it possible for user bits to be mapped straight into codewords. According to this definition, the generic SCMA encoding process can be shown in Figure 1.

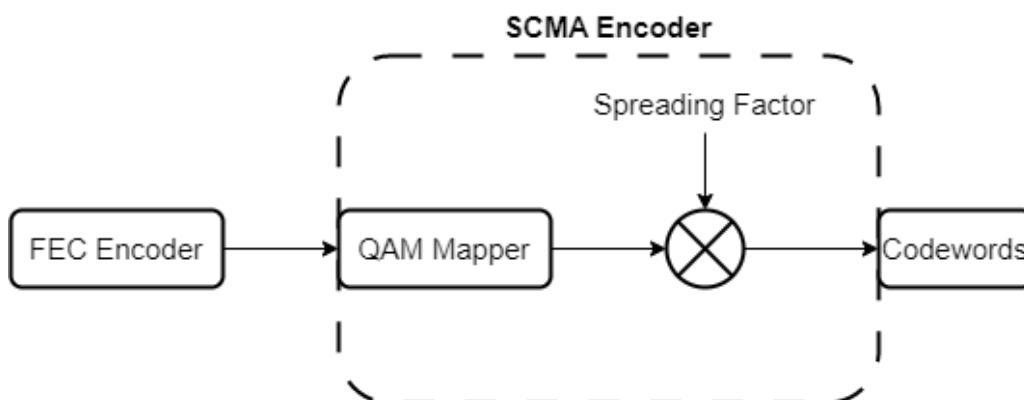


Figure 2.1 Generic SCMA Encoder

Information bits are first passed to the Forward Error Correction (FEC) encoder, which is a way of detecting transmission errors without re-transmitting data. After that, encoded bits are passed on to the SCMA encoder to map the bits to codewords using each user's codebook.

An example of the SCMA system is presented in Figure 2, where squares denote users and circles denote sub-carriers.

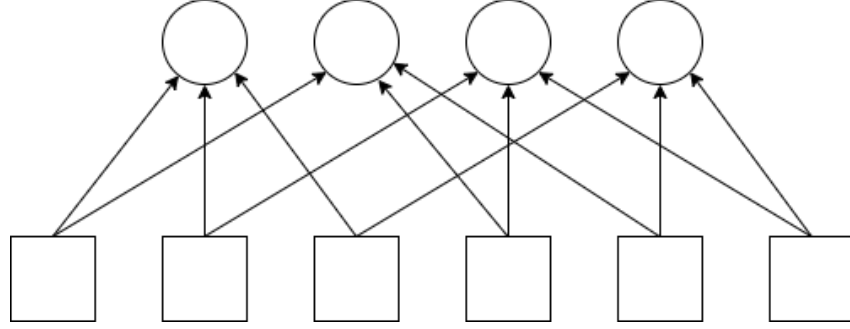


Figure 2.2 SCMA System Structure

From Figure 2, each user shares frequency resources equally, which means each user uses the same number of resources, and the same number of users uses each resource; thus, an SCMA system is said to be homogeneous. In an SCMA system, there are J users and K sub-carriers, and each user's codebook is K dimensional and consists of J codewords. Non-zero elements in a codeword are denoted as N . In this context $N < K$ denotes sparsity and $J > K$ denotes overloading. Overloading is commonly denoted as λ . Due to the non-orthogonality of SCMA systems, it is always expected that $\lambda > 1$. Figure 2 is commonly expressed in terms of a matrix called Factor Graph matrix, and it also denotes the connection between sub-carriers and users. For a system with $J = 6$ and $K=4$, Factor Graph matrix can be shown as

$$\mathbf{F} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix} \quad (2.1)$$

According to the matrix above, each user occupies $d_v = 2$ sub-carriers, and each sub-carrier is occupied by $d_f = 3$. In this sense signal in the k^{th} , sub-carrier can be expressed as

$$y_k = \sum_{j=1}^J h_{kj}x_{kj} + n_{kj} \quad (2.2)$$

where x_{kj} denotes the k^{th} element of j^{th} user at codeword x , h_{kj} denotes the j^{th} users channel coefficient at k^{th} sub-carrier and n_k denotes the complex noise at the k^{th} sub-carrier.

Extending the above equation to the whole system, total received signal can now be expressed as

$$\mathbf{y} = \sum_{j=1}^J \text{diag}(h_j)x_j + \mathbf{n} \quad (2.3)$$

where $x_j = (x_{1j}, x_{2j}, \dots, x_{Kj})^T$ denotes the codeword that belongs to j^{th} user, $h_j = (h_{1j}, h_{2j}, \dots, h_{Kj})^T$, denotes channel coefficient vector that belongs to $j; th$ user and $n \propto CN(0, \sigma^2 I_k)$ denotes Gaussian noise.

2.2 Symbol Detection with Message Passing Algorithm (MPA)

Encoded bits defined by the equation (2.3) are passed through sub-carriers and need to be decoded. One of the popular ways to detect the symbols is the use Maximum Likelihood (ML) approach, downside to this is that time complexity of ML approach increases exponentially by the number of users and polynomially by the size of the codebook, that is $O(M^J)$ [11]. This approach tends to lose its practicality for realistic scenarios where number of users are big and size of the codebook is large. Fortunately there is another approach called Message Passing Algorithm. MPA is an iterative approach in which probability of information bits are updated in every function node (sub-carriers) and variable node (users). Biggest benefit of this approach is that, due to the sparsity of the codebook, it can achieve ML like results, with enough iterations, while having much lower time complexity, $O(M^{d_f})$ [24]. MPA can directly work on a factor graph such as (2.1). As mentioned before in terms of MPA decoding users and sub-carriers are treated as nodes, and in each iteration information on received signal is updated and at the end of each iteration probability estimations of codebooks are obtained, after all of the iterations are

exhausted, algorithm outputs Log Likelihood Ratio (LLR), from where information bits of each users is determined.

MPA decoding first starts by calculating the initial conditional probability, to do so for each sub-carrier (e.g function node) sets of residual signals with known channel coefficients and codewords are calculated as

$$f_n(y_n, m_1, m_2, m_3, N_{0,n}, H_n) = \frac{-1}{N_{0,n}} ||y_n - (h_{n,1}C_{1,n}m_1 + h_{n,2}C_{2,n}m_2 + h_{n,3}C_{3,n}m_3)||^2 \quad (2.4)$$

where $h_{n,k}$ is known or estimated channel and $C_{k,n}$ is assumed codeword, therefore conditional probability for a codeword combination ϕ_n can be written as,

$$\phi_n = exp(f_n(y_n, m_1, m_2, m_3, N_{0,n}, H_n)) \quad (2.5)$$

This also implies that for a gaussian noise case conditional probability is just exponential operation of equation in (2.4). Initially each codeword has equal prior probability, this assumption helps the preparation of first step for iteration. This prior probability equality can be shown as,

$$I_{V_1 \rightarrow g}^{init} = I_{V_2 \rightarrow g}^{init} = I_{V_3 \rightarrow g}^{init} = \frac{1}{M} \quad (2.6)$$

After calculating initial conditional probability, MPA starts an iterative message passing processes between function nodes and variable nodes, note that information exchange only happens between nodes that are connected to each other. A function node sends updates to its neighboring variable nodes obtained from extrinsic information, this can be represented as

$$I_{g \rightarrow V_1}(m_1) = \sum_{m_2=1}^M \sum_{m_3=1}^M \phi(y_n, m_1, m_2, m_3, N_{0,n}, H_n) (I_{V_2 \rightarrow g}(m_2) I_{V_3 \rightarrow g}(m_3)) \quad (2.7)$$

Similarly each variable node "v" sends updates on information to its neighboring function nodes, this process can be written as

$$\begin{aligned} I_{V \rightarrow g_1}(m) &= \text{normalize}(ap_v(m) I_{g_2 \rightarrow V}(m)) \\ I_{V \rightarrow g_2}(m) &= \text{normalize}(ap_v(m) I_{g_1 \rightarrow V}(m)) \end{aligned} \quad (2.8)$$

These function node and variable node updates are done iteratively until number of MPA iterations are exhausted.

As a last step iterative process mentioned above outputs a chain of guesses for each variable nodes obtained from neighboring function nodes

$$Q_v(m) = ap_v(m) I_{g_1 \rightarrow V}(m) I_{g_2 \rightarrow V}(m) \quad (2.9)$$

After getting guesses from each variable nodes Log Likelihood Ratio (LLR) needs to be calculated for each coded bit such as

$$LLR_x = \log\left(\frac{P(b_x = 0)}{P(b_x = 1)}\right) \quad (2.10)$$

$$LLR_x = \log\left(\frac{\sum_{m:b_{m,x}=0} Q_v(m)}{\sum_{m:b_{m,x}=1} Q_v(m)}\right) = \log\left(\sum_{m:b_{m,x}=0} Q_v(m)\right) - \log\left(\sum_{m:b_{m,x}=1} Q_v(m)\right) \quad (2.11)$$

3. FAST FADING RAYLEIGH CHANNELS

This chapter investigates effect of both Flat and Fast Fading Rayleigh Channels on the Bit Error Rate (BER) of SCMA systems.

3.1 Channel Model

3.1.1 Flat fading

In a Flat Fading channel model, the channel's coefficients are assumed to be constant through a symbol duration, e.g Quasi-static. Channel follows Gaussian Distribution with mean μ and variance σ^2 , that is $N(\mu, \sigma^2)$, for the sake of simplicity and consistency it is assumed that $\mu = 0$ and $\sigma^2 = 1$.

3.1.2 Fast fading

In Fast Fading, channel coefficients are not constant through a symbol duration, similar to Flat Fading channel coefficients follow Gaussian Distribution $N(0, 1)$. In Figure 3.1 [25], change of channel coefficient h n times during a symbol time s is presented.

Assuming all of the channel coefficients and channel changing times are known effect of fast fading in SCMA systems in terms of BER can be seen in Figure 3.2.

3.2 Correlated Fast Fading Channels

In 3.1.2, channel coefficients after each change are independent of each other, therefore pose no correlation. To give a more realistic case of fast fading in this subsection, a correlated case of fast fading is presented in this subsection with different cases of

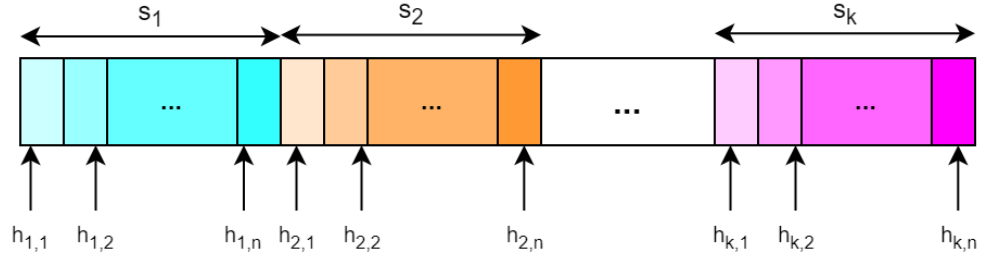


Figure 3.1 Fast Fading Rayleigh Channel

correlation. Correlated channel coefficients are generated by first creating a random channel coefficient matrix \mathbf{h} , and then for a correlation coefficient σ , a 2×2 correlation matrix \mathbf{R} is initialized finally, correlated channel coefficients are obtained by multiplying \mathbf{h} with Cholesky Decomposed Matrix \mathbf{R} .

3.3 High Rate MPA (HR-MPA)

It is no surprise that SCMA would perform poorly under the influence of fast fading; this is because MPA works on the last known channel coefficients to decode the incoming signal, to overcome this High Rate, MPA (HR-MPA) is proposed, with this method, MPA adapts on the changing channel coefficients and decodes the signal at the end of each coefficient change. Therefore It should be noted that time complexity of the HR-MPA linearly increases with the number of coefficient changes that is $O(NM^{df})$, where N is fast fading rate. HR-MPA algorithm is presented in Algorithm 1.

Algorithm 1 High Rate Message Passing Algorithm

Input: Changing channel coefficients - h_i

Output: Decoded bits for each changing channel coefficients

```
1: for  $s_j = [s_1, s_2, \dots, s_k]$  do
2:   for  $h_i = [h_1, h_2, \dots, h_n]$  do
3:     execute MPA
4:   end for
5:    $s_j \leftarrow \sum_1^n s_{j,i}$ 
6: end for
```

3.4 Numerical Results

In Figure 3.2, the effect of fast fading with rates 2, 3, and 4 is presented. As can be seen from the figure at BER 10^{-2} SCMA system experiences a loss of 3dB, 5dB, and 6dB, respectively.

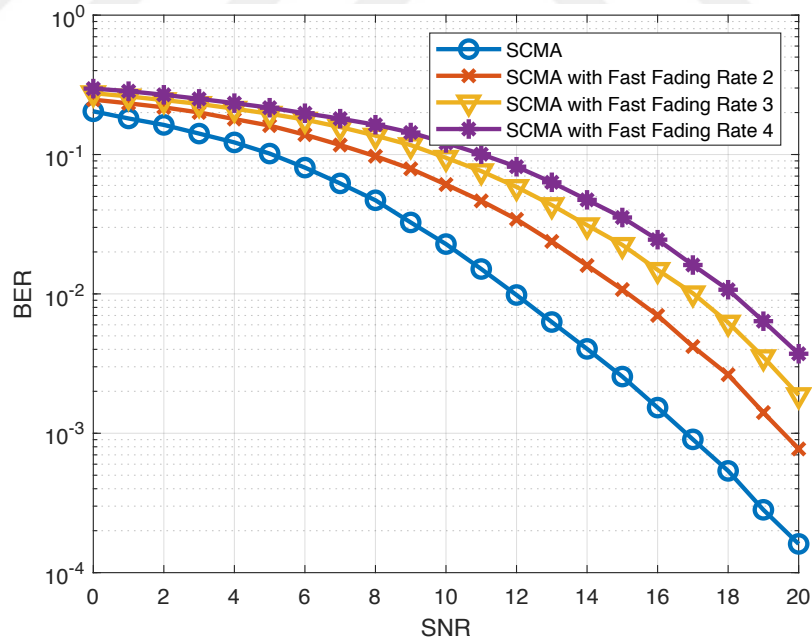


Figure 3.2 Effect of Fast Fading on SCMA

As can be seen from 3.2, performs visibly poor under the influence of fast fading to compensate for the error margin caused by this phenomenon, as mentioned in

previous sub-sections, High Rate MPA was employed for different fast fading rates.

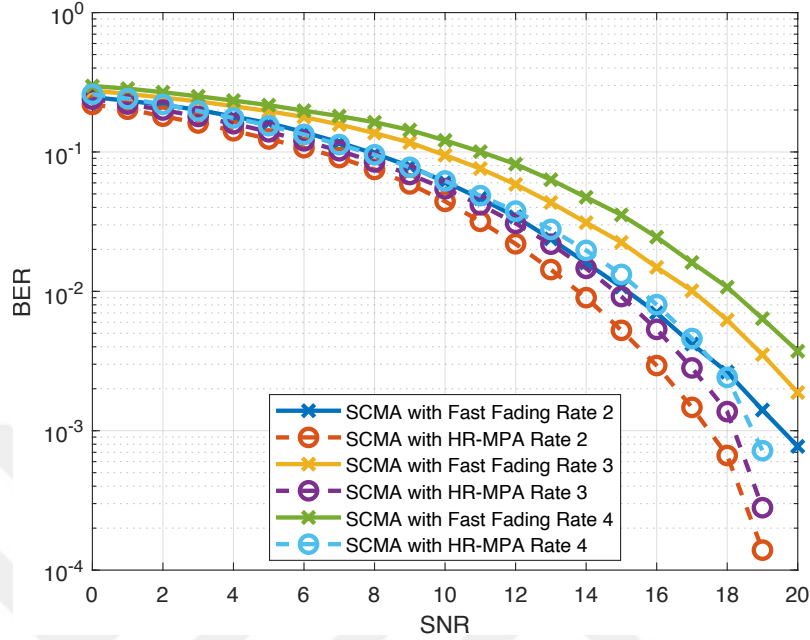


Figure 3.3 HR-MPA

Figure 3.3 shows the effect of HR-MPA when SCMA is exposed to fast fading, with the help of HR-MPA at BER 10^{-2} a gain of 1dB, 2dB and approximately 2.5dB can be obtained for fast fading rates 2,3 and 4 respectively. This is because, after every channel coefficient change, the iterative decoder at the receiver adapts to new channel coefficients and decodes the encoded signal accordingly. In a more realistic scenario where SCMA transmissions happen when the channel is subject to fast fading, these coefficients would be correlated, in Figure 3.4, correlated coefficients with fast fading are presented where correlation coefficient $\sigma = 0.9$. When compared to the first scenario, where channel coefficients pose no correlation, correlated scenario performs almost similar to the flat fading case.

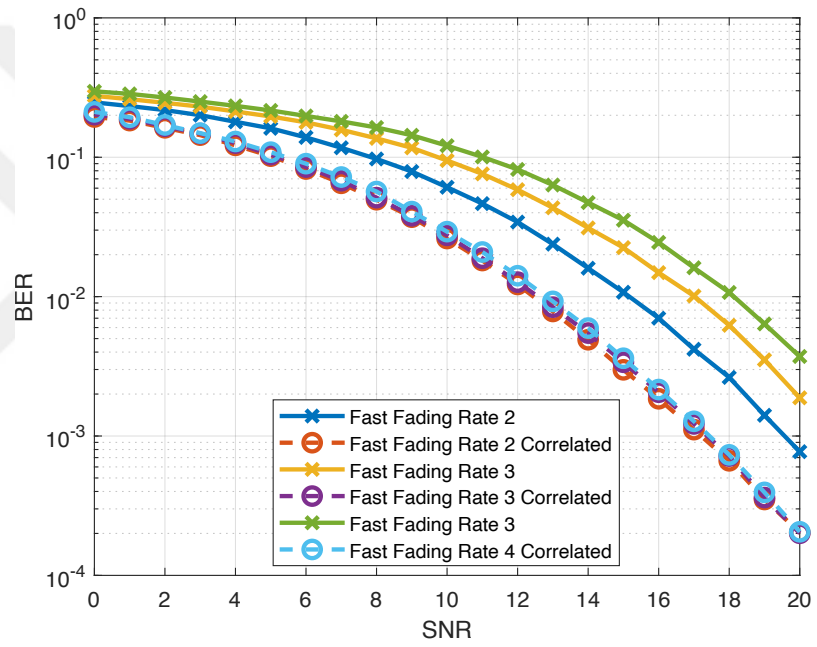


Figure 3.4 Correlated Channel

4. CHANNEL ESTIMATION

In a wireless communication system, in order to establish a reliable connection between transmitters and receivers channel coefficients \mathbf{h} should be known, or appropriately estimated by the receiver. Channel estimation can be conducted in various ways and channel estimation techniques can be classified in three main categories as [26]

- Blind Channel Estimation
- Semi-Blind Channel Estimation
- Training Based (Pilot Aided) Channel Estimation

This chapter investigates the effect of estimated channels on the performance of SCMA systems with a sole focus on pilot-aided estimation with both orthogonal and non-orthogonal pilots as well as non-orthogonal pilot generation using Genetic Algorithms (GA).

4.1 Pilot Aided Channel Estimation

Pilot Aided Channel Estimation (PACE), is a process of adding symbols (pilots) that are known by both transmitter and receiver, with this receiver can estimate the channel anytime anywhere provided sampling rate is enough compared to the channel bandwidth [27], with pilots are known, channel can be estimated using Least Squares Estimation.

Suppose received pilot signal at the receiver is

$$\mathbf{y}_{pilot} = \mathbf{P}\mathbf{h} + \mathbf{n} \quad (4.1)$$

where \mathbf{y}_{pilot} is received pilot signal, \mathbf{P} is pilot signal matrix, \mathbf{h} is channel coefficients and \mathbf{n} is noise.

Assuming noise is identically and independently distributed Gaussian random variable having $\mu = 0$ mean and $\sigma^2 = 1$ variance, that is $\mathbf{n} \stackrel{iid}{\sim} \mathcal{N}(0, 1)$, then probability density function (PDF) can be written as

$$P = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\mathbf{n}^2}{2\sigma^2}} \quad (4.2)$$

using equation (4.2) probability of \mathbf{y}_{pilot} given pilot matrix \mathbf{P} and \mathbf{h} can be represented as

$$P(\mathbf{y}|\mathbf{P}; \mathbf{h}) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(\mathbf{y}-\mathbf{hP})^2}{2\sigma^2}} \quad (4.3)$$

using equation (4.3) likelihood function becomes

$$\mathcal{L}(\mathbf{h}) = \prod_{i=1}^L \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(y_i - \mathbf{h}P_i)^2}{2\sigma^2}} \quad (4.4)$$

taking the logarithm and factoring (4.4)

$$\sum_{i=1}^L \log \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(y_i - \mathbf{h}P_i)^2}{2\sigma^2}} \quad (4.5)$$

$$L * \log \frac{1}{\sqrt{2\pi\sigma^2}} - \frac{1}{2\sigma^2} \sum_{i=1}^L (y_i - \mathbf{h}P_i)^2 \quad (4.6)$$

from (4.6) cost function \mathbf{J} is

$$J(\mathbf{h}) = \frac{1}{2} \sum_{i=1}^L (y_i - \mathbf{h}P_i)^2 \quad (4.7)$$

using the property $z^T z = \sum z_i$ cost function in (4.7) can be re-written as

$$J(\mathbf{h}) = \frac{1}{2} (\mathbf{y} - \mathbf{P}\mathbf{h})^T (\mathbf{y} - \mathbf{P}\mathbf{h}) \quad (4.8)$$

equation in (4.8) can be minimized by taking its gradient with respect to \mathbf{h}

$$\nabla_{\mathbf{h}} J(\mathbf{h}) = \nabla_{\mathbf{h}} \frac{1}{2} (\mathbf{y} - \mathbf{P}\mathbf{h})^T (\mathbf{y} - \mathbf{P}\mathbf{h}) = \mathbf{P}^T \mathbf{P}\mathbf{h} - \mathbf{P}^T \mathbf{y} \quad (4.9)$$

after factoring (4.9) it can one can obtain

$$\mathbf{h} = (\mathbf{P}^T \mathbf{P})^{-1} \mathbf{P}^T \mathbf{y} \quad (4.10)$$

4.2 Channel Model

Channel is assumed to follow an Uplink Rayleigh Fading with block fading model that is similar to studies in [28], [29] with for each user j in the system, channel coefficients \mathbf{h}_j are stationary at each resource block and only vary for different resource blocks. It is also assumed that pilot symbols L codewords are randomly placed in each resource block since the pilot symbol allocation is not considered.

4.3 Genetic Algorithm Based Pilot Design

In this section, first the optimization problem is presented with non-orthogonal pilots, and then pilot design using GA is provided.

4.3.1 Optimization problem

Genetic Algorithms are one of the heuristic optimization algorithms in that in each iteration, the algorithm keeps the best individuals. It discards the non-desirables, and with the best solutions using specific crossover and mutation operators algorithm tries to create better solutions. The algorithm needs an objective function to determine how well a solution performs given a problem. In this case, the fitness function f is the Mean Squared Error between the actual and the estimated channel coefficients; \mathbf{h} , $\hat{\mathbf{h}}$. In that case, f becomes

$$\min_{h, \hat{h}} E_h[(\hat{h} - h)^2] \quad (4.11)$$

The pilot matrix \mathbf{P} has a $L \times J$ size, with each user having $L/2$ non-zero pilot symbols. It should be noted that since GA's can only work with real-valued parameters and \mathbf{P} is a complex matrix, there are $(2LJ)/2$ parameters that need to be optimized, an example of \mathbf{P} with $L = 8$ can be written as follows.

$$\mathbf{F} = \begin{bmatrix} 0 & \mathbf{z}_5 & \mathbf{z}_9 & 0 & \mathbf{z}_{17} & 0 \\ \mathbf{z}_1 & 0 & \mathbf{z}_{10} & 0 & 0 & \mathbf{z}_{21} \\ 0 & \mathbf{z}_6 & 0 & \mathbf{z}_{13} & 0 & \mathbf{z}_{22} \\ \mathbf{z}_2 & 0 & 0 & \mathbf{z}_{14} & \mathbf{z}_{18} & 0 \\ 0 & \mathbf{z}_7 & \mathbf{z}_{11} & 0 & \mathbf{z}_{19} & 0 \\ \mathbf{z}_3 & 0 & \mathbf{z}_{12} & 0 & 0 & \mathbf{z}_{23} \\ 0 & \mathbf{z}_8 & 0 & \mathbf{z}_{15} & 0 & \mathbf{z}_{24} \\ \mathbf{z}_4 & 0 & 0 & \mathbf{z}_{16} & \mathbf{z}_{20} & 0 \end{bmatrix} \quad (4.12)$$

where

$$\mathbf{z}_i = \alpha_i + j\beta_i, i = 1, 2, \dots, ((2LJ/2) - 1) \quad (4.13)$$

4.3.2 Non-orthogonal pilot design

The pilot matrix \mathbf{P} is optimized using MATLAB's built-in genetic algorithm toolbox *ga*. Mainly default parameters were used for algorithms crossover and mutation operators, and the binary tournament was used for the selection algorithm. Each generation had 300 population in the optimization process, and the algorithm was run until 50 iterations were reached. Each parameter in the algorithm had a bound of

$$-1 \leq \alpha_i \leq 1, i = 1, 2, \dots, ((2LJ/2) - 1) \quad (4.14)$$

$$-1 \leq \beta_i \leq 1, i = 1, 2, \dots, ((2LJ/2) - 1) \quad (4.15)$$

The initial parameters were created randomly between the two given bounds above; also, each parameter was normalized such that the energy of \mathbf{P} is unity.

4.4 Numerical Results

This section presents the BER performance comparison of the pilots' signals generated using genetic algorithms and non-orthogonal pilots from [29], obtained from the conventional codebook [30] using a brute force algorithm. To compare the two pilot signals fairly, both of the pilot's average powers are normalized to unity. In Figure 4.1, BER simulation results when pilot length eight is shown, while the performances are similar with the pilots from the literature when the pilot length is increased, i.e., in the case when the pilot length is 12 in Figure 4.2 at BER 10^{-3} , proposed method results in a 1dB gain.

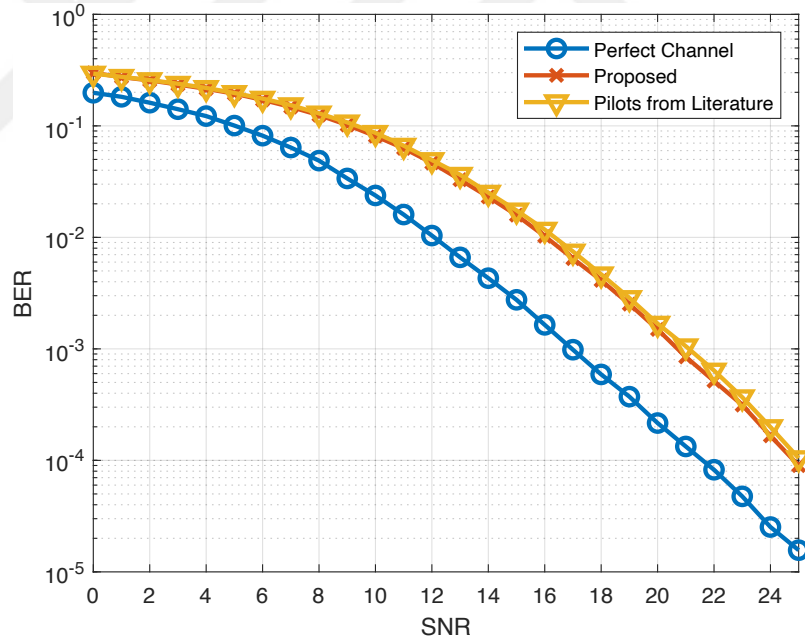


Figure 4.1 Estimated Channel with Pilot Length 8

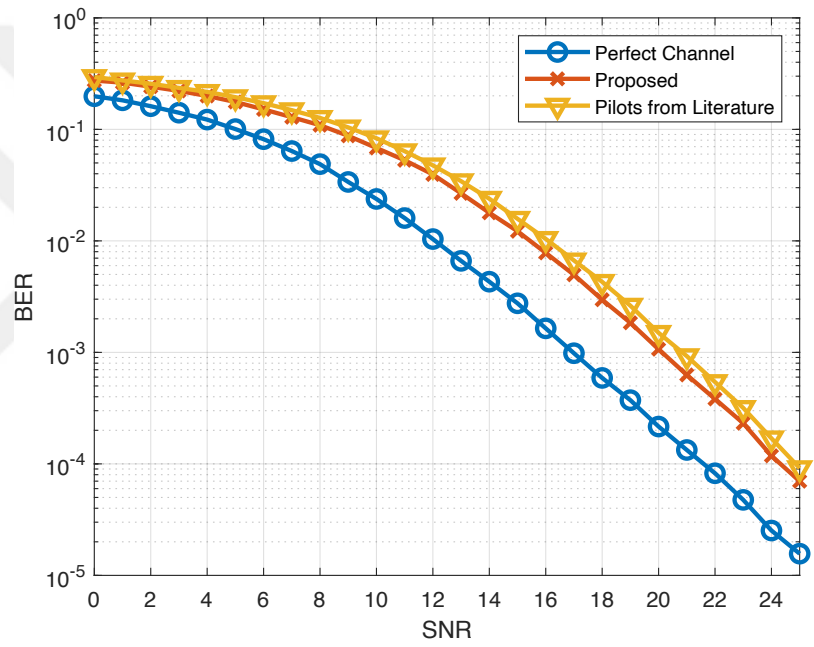


Figure 4.2 Estimated Channel with Pilot Length 12

5. PN SEQUENCES & INTERSYMBOL INTERFERENCE

This chapter investigates the adverse effects of Intersymbol Interference (ISI) on SCMA systems and the use of Pseudorandom Noise (PN) sequences to mitigate these effects.

5.1 PN Sequences

Pseudorandom noise (PN) sequences mimic actual signal noises and seem entirely random, thanks to their statistical similarities to actual random noises. However, these sequences are deterministic and start to repeat themselves after a long enough time, and since they naturally have good autocorrelation properties interfering with them is pretty challenging. Because of this, PN sequences can find many applications, from cryptography to telecommunications.

5.1.1 PN sequence generation

PN Sequences are generated through Linear Feedback Shift Registers (LSFR). For an LSFR with m number of registers, the output sequence depends on m and initial state and also it should be noted that the maximum period of a PN sequence is $2^m - 1$. An example of LSFR with a state polynomial $z^6 + z + 1$ is given at Figure 5.1

To incorporate PN sequences into an SCMA system, user information bits with PN sequences need to be spread. As mentioned in 5.1 before received signal at k^{th} sub-carrier can be written as:

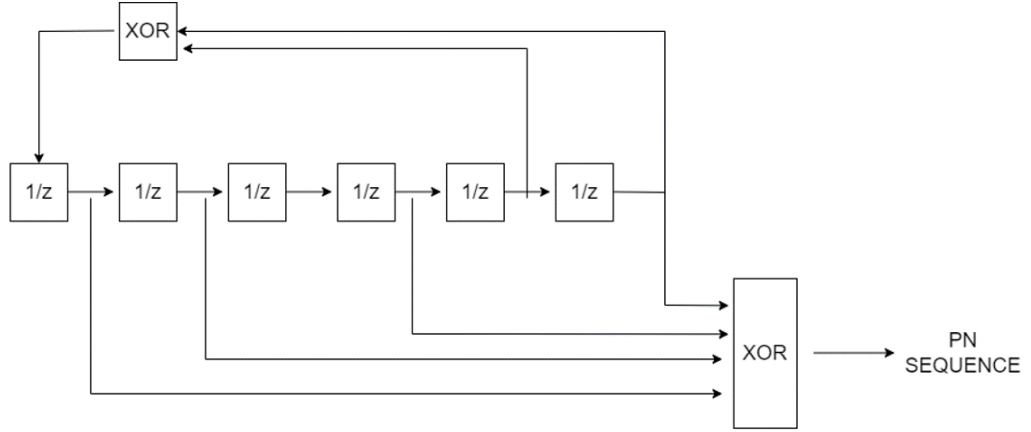


Figure 5.1 A Linear Feedback Shift Register

$$y_k = \sum_{j=1}^J h_{kj} x_{kj} + n_{kj} \quad (5.1)$$

therefore a received spread signal at k^{th} sub-carrier is:

$$y_k = \sum_{j=1}^J h_{kj} x_{kj} z_j + n_{kj} \quad (5.2)$$

where z_j is the spread sequence belonging to the j^{th} user. After MPA decoding process, decoded bits need to be de-spread which can be expressed as:

$$bits = \sum_{j=1}^J \sum_{i=1}^{|z|} LLR_{ji} * z_i \quad (5.3)$$

whole SCMA system regarding spreading and de-spreading can be shown as in 5.2

5.2 Intersymbol Interference

Intersymbol interference (ISI) is a communication phenomenon where transmitted symbols interfere, resulting in a degradation in transmitted signal quality. ISI can

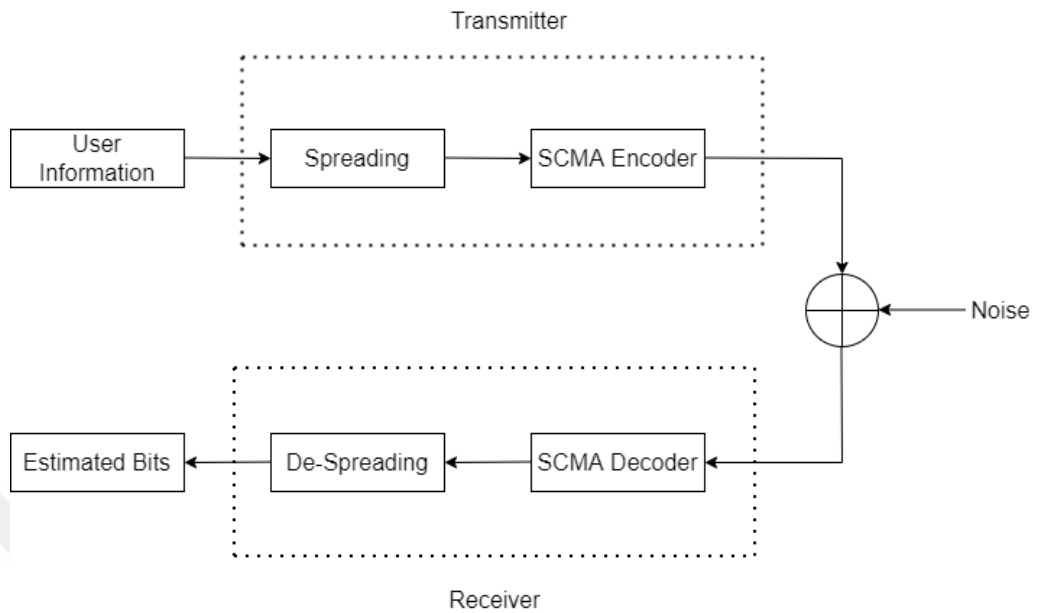


Figure 5.2 SCMA System with PN Sequences

occur due to multipath propagation or limitations in the bandwidth of the channel. While ISI decreases the chances of correctly decoding the transmitted signal, the adverse effects of ISI can be mitigated to some degree by adding redundant bits to the signal.

5.3 Numerical Results

In this chapter, numerical results regarding the effects of ISI on the SCMA systems and the gain obtained by using PN sequences with different lengths are provided. Each simulation was run for six users and four sub-carriers, and there were 1024 SCMA signals in each frame. Figure 6.3 shows how severely SCMA is affected by the ISI; at 102 BER, the SCMA system has approximately 4dB loss.

In Figure 5.4, PN Sequences with respective lengths 6 and 8 were used to cover the effect of PN sequences on SCMA systems exposed to ISI. For PN sequence length 6, SCMA systems performance improves by 1dB at BER 10^{-2} , and for PN sequence length 8, performance improves by 2dB at BER 10^{-2} by 2dB compared to

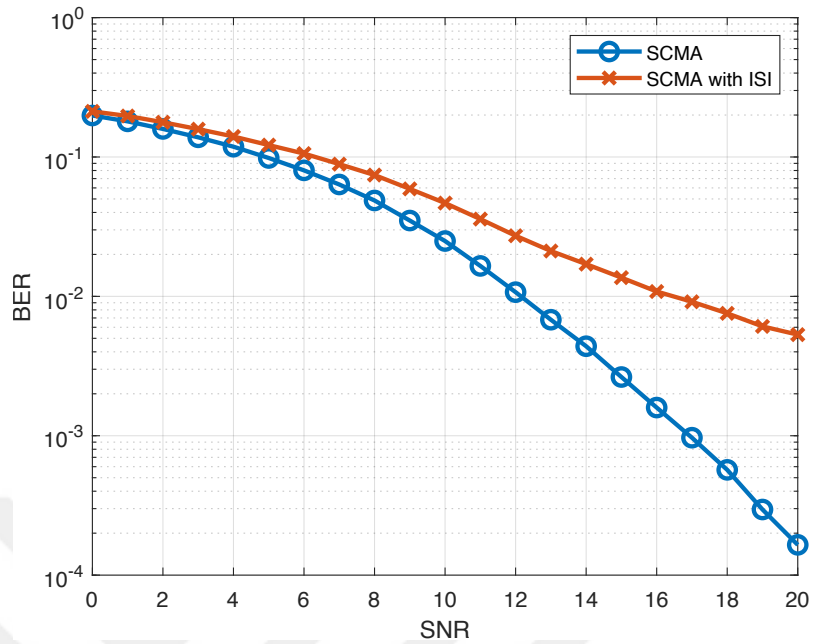


Figure 5.3 Effect of ISI on SCMA

the ISI case. Also, the experiments have shown that, in order to obtain consistent results and visible improvements PN Sequences of length should be fixed to at least a minimum of 6, and since PN Sequences are used to add redundant bits to the actual user information, the number of bits that need to be decoded at the receiver thus increasing the decoding time which PN Sequence length should be carefully selected for a trade-off between performance and service time.

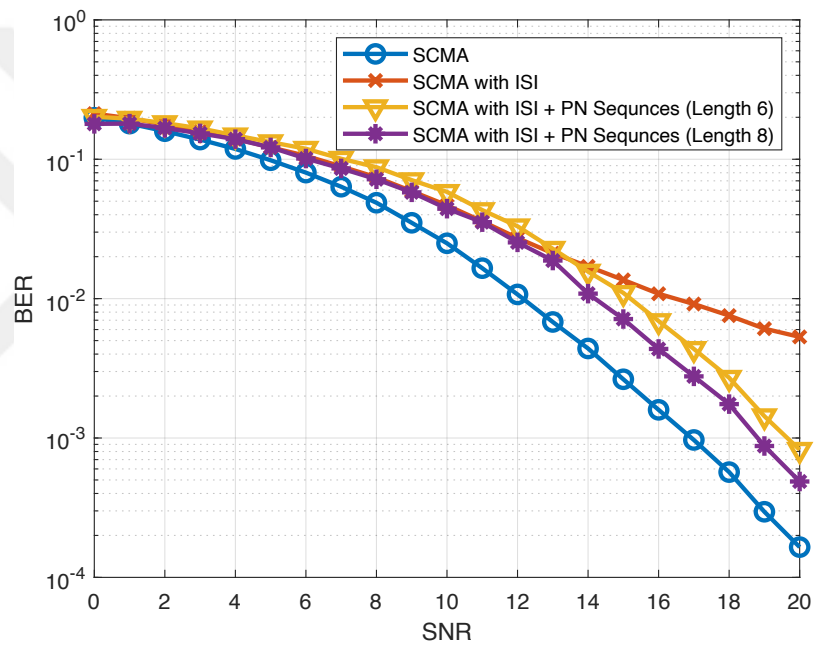


Figure 5.4 Effect PN Sequences on SCMA Systems with ISI

6. CODEBOOK DESIGN

An SCMA codebook is the primary factor that defines how well a connection can be established between sub-carriers and users, such that for an uncoded conventional SCMA system a codebook is responsible most of the transmission errors, also an SCMA codebook is also responsible for user allocation, that is deciding which user will establish a connection to which sub-carrier is up to the codebook. There are numerous studies in the literature that propose different methodologies for creating codebooks. Usually for an SCMA system with K sub-carriers, J users and modulation order M , a codebook is created in two steps, these are:

1. Creating an optimized multidimensional mother constellation (C_{MC}) that have acceptable error rates.
2. Obtaining user specific codebooks from C_{MC} by using spreading and phase operator matrices.

A spreading matrix \mathbf{V} is a binary matrix with $\mathbf{V} \in \mathcal{B}^{K \times N}$ and a phase operator matrix Δ is a complex matrix with $\Delta \in \mathcal{C}^{N \times N}$, where N is the dimension of mother constellation.

Most of the studies propose a codebook for either AWGN or Rayleigh fading channels and how to design an optimal codebook that can produce exceptional error rates in all types of channels is still remain a mystery. Vameghestahbanati et al. [31] provides a list of key performance indicators (KPI) for codebooks according to this KPI's that have the major impact on the performance can be summarized as:

- Minimum Euclidean Distance (MED)
- Minimum Product Distance (MPD)
- Euclidean Kissing Number

- Product Kissing Number

MED ($d_{E,min}$) is the euclidean distance between codewords in a C_{MC} , x_m and x_n where $1 \leq m < n \leq M$, but in recent years it is shown that rather than using MED of codewords in a C_{MC} , MED of superimposed codewords in a whole SCMA system produces better results [32], [33], [19], also MED has the biggest impact on the performance of SCMA systems for AWGN channels [34].

MPD ($d_{P,min}$) is the product of distances between dimensions of codewords in a C_{MC} and influences error rate performances significantly [35], for codewords x_m and x_n product distance is defined as:

$$d_P^{mn} = \prod_{j=1}^{d_v} |x_{mj} - x_{nj}| \quad (6.1)$$

where $1 \leq m < n \leq M$ so MPD is:

$$d_{P,min} = \min\{d_P^{mn} | 1 \leq m < n \leq M\} \quad (6.2)$$

Euclidean Kissing Number (τ_E) is the number of pairs of codewords that have an MED of $d_{E,min}$.

Product Kissing Number (τ_P) is the number of pairs of codewords that have an MPD of $d_{P,min}$.

According to the KPI's provided above, in order to optimize a C_{MC} one must maximize MED and MPD, and minimize Euclidean and Product Kissing Number.

6.1 Genetic Algorithm Based Codebook Design

Genetic Algorithms (GA) are iterative heuristic optimization algorithms inspired by the evolution theory. GA's have five different phases, these are,

- Initial population creation, where the first generation is usually generated randomly
- Fitness Evaluation, where each solution in the generation set is evaluated based on how well they perform with respect to the objective functions.
- Selection, where solutions in the generations are selected pair-wise as parents using various algorithms such as binary tournament.
- Crossover, where selected pairs from the previous phase are crossed over to generate off-springs for the next generations; some popular crossover algorithms are SBX Crossover, one-point and two-point crossover.
- Mutation, where some of the chromosomes (values each solution holds) are mutated randomly to make it easier for the algorithm to explore a more comprehensive solution space.

Two of the most prevalent genetic algorithms are NSGA-II [36] and SPEA-2 [37]. NSGA-II provides a computationally less expensive approach than SPEA-2, but SPEA-2 can provide a more comprehensive search space, thus increasing the diversity of the solutions. This thesis investigates using SPEA-2 for mother codebook optimization as a multi-objective optimization problem.

6.1.1 Formulation of the problem

The structure of a mother constellation acts as a starting point and can actually help the genetic algorithm converge faster to an optimized codebook. Studies in the literature have shown that selecting the structure of the mother constellation as Star-QAM can lead to better results [38], [21], for a mother constellation having 2-dimensions and an SCMA system with $M = 4$, Star-QAM mother constellation

has the form:

$$\mathbf{C}_{MC} = \begin{bmatrix} \alpha z_1 & z_1 & -z_1 & -\alpha z_1 \\ -z_2 & \alpha z_2 & -\alpha z_2 & z_2 \end{bmatrix} \quad (6.3)$$

where z and α have bounds:

$$\begin{aligned} -1 &\leq \Re(z) \leq 1 \\ -1 &\leq \Im(z) \leq 1 \\ |\alpha| &\leq 1 \end{aligned} \quad (6.4)$$

it should be noted that α is a real and z is a complex number. Most studies have tried to maximize MED and MPD while keeping Euclidean and product kissing numbers as low as possible. However, since the mother constellation that needs to be optimized is specific to SCMA systems, similar to [23], it is possible to use SCMA Monte Carlo simulations as objective functions. One of the biggest upsides of this approach is that it considers the effect of the MPA decoding process. Since the objective functions of genetic algorithms need not be in closed form, genetic algorithms are a perfect cut for this. Most of the studies mentioned in previous chapters treat the codebook optimization problem in a channel-dependent way; that is, they optimize the codebook for specific channels. This type of approach poses a problem in which makes the codebooks only suitable for one channel making it less performant in the channels that they were not designed for. This thesis investigates the use of genetic algorithms for the creation of channel-independent codebooks. As mentioned before, user-specific codebooks are obtained through spreading and phase-operator matrices; for spreading matrix \mathbf{V} and phase operator matrix Δ , user j 's codebook can be created with the equation $\chi_j = \mathbf{V}_j \Delta_j C_{MC}$.

An example of a spreading matrix and phase operator matrix for an SCMA system with $M = 4$, $N = 2$, and $K = 4$ can be represented as

$$\mathbf{V}_j = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (6.5)$$

$$\Delta_j = \begin{bmatrix} e^{j\varphi_1} & 0 \\ 0 & e^{j\varphi_2} \end{bmatrix} \quad (6.6)$$

where φ_i in 6.6 can be any arbitrary number between $0 \leq \varphi_i < 2\pi$, and $1 \leq i \leq d_f$. According to the information presented above the optimization problem turned into a multi-objective minimization problem and can be formulated as:

$$\begin{aligned} & \min_{\varphi, C_{MC}, h_{AWGN}} f_{AWGN}(\varphi, C_{MC}, SNR) \\ & \min_{\varphi, C_{MC}, h_{Rayleigh}} f_{Rayleigh}(\varphi, C_{MC}, SNR) \\ & \min_{\varphi, C_{MC}, h_{Nakagami}} f_{Nakagami}(\varphi, C_{MC}, SNR) \\ & 0 < \varphi_i < 2\pi, \forall i = 1, 2, \dots, d_f \\ & h_{Rayleigh} \sim \mathcal{N}(0, \sigma^2) \\ & h_{Nakagami} \sim \mathcal{G}(0, \sigma^2) \\ & h_{AWGN} \end{aligned} \quad (6.7)$$

where f is the objective function (in this case whole Monte-Carlo SCMA simulation), and to cover as many channels as possible, three different types of channels were selected: Rayleigh channel, Nakagami-2 channel, and AWGN channel.

6.1.2 Optimization method

To solve the problem in 6.7, SPEA-2 type genetic algorithm was employed. Binary tournament selection algorithms were used for selection and for crossover and

mutation, SBX Crossover and Polynomial Mutation were used, respectively. SBX Crossover and Polynomial mutation need a user-defined input variable called η . The experiments have shown that setting η_C for crossover and η_m for mutation 10 leads to better results; the optimization algorithm was run for 35 iterations, and the initial population set had 200 individuals, also a problem in 6.7 requires a hand-picked SNR value, conducted experiments have shown that higher SNR values lead to a better-optimized codebook, for this purpose SNR is selected as; 8dB, 14dB and 9dB for AWGN, Rayleigh and Nakagami-2 channels, respectively. Selected channels for the optimization problem conflict with each other because of their distributions. This conflict will likely lead to a situation where for a codebook that is optimal for a channel might have higher BER results than others. This problem is further explained in a Pareto-Optimal Front of the result of the genetic algorithm. A Pareto-Optimal Front includes all of the feasible solutions of a problem.

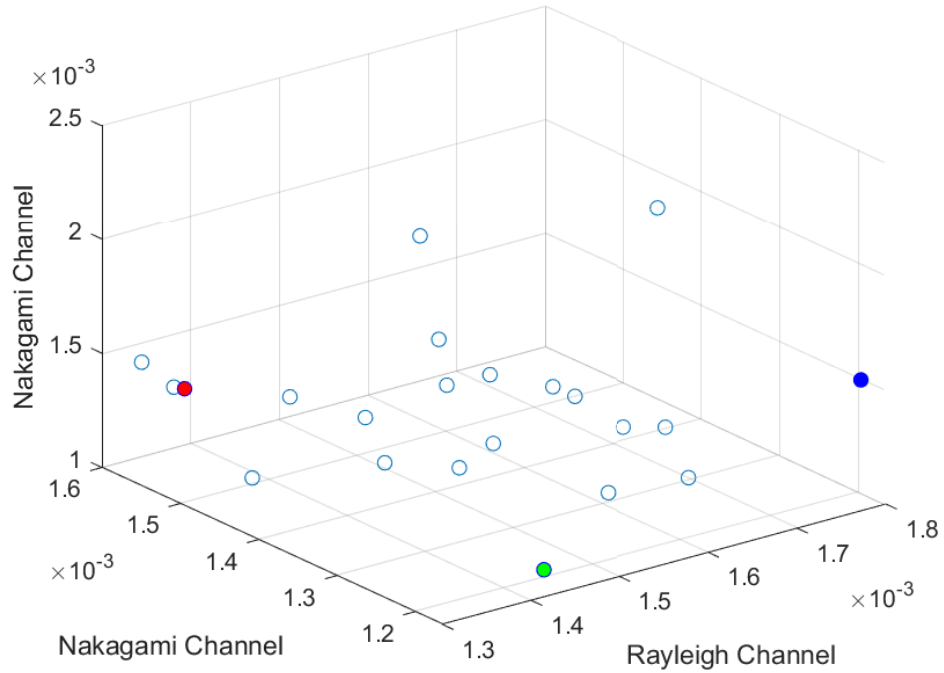


Figure 6.1 Example of feasible solutions in a 3D Pareto Optimal Front

From figures 6.2, 6.3, and 6.4 the conflict of channel types can clearly be seen, because of this we selected 3 codebooks namely Pareto Codebook 1, 2, and 3, where

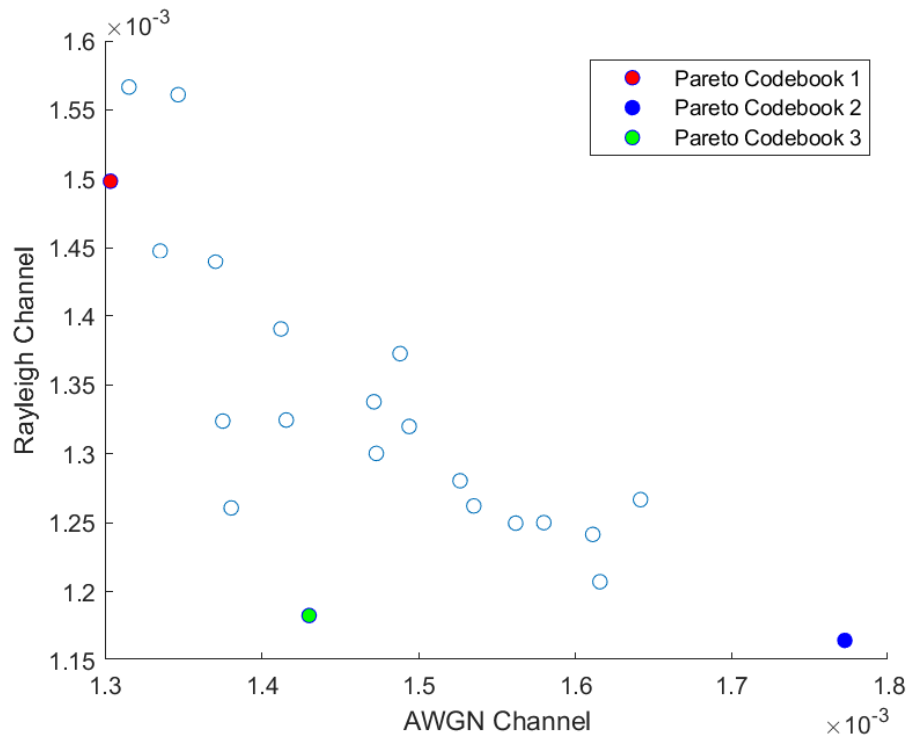


Figure 6.2 BER distribution of AWGN and Rayleigh Channels

selected codebooks are the top performers in their respective channels.

6.2 Numerical Results

In this section, the BER performance of the produced codebook for Rayleigh, AWGN, Nakagami-2, and Ricean channels is presented and compared with the codebook from [30], [21], [19], [39], and [22]. Even though Ricean fading was not included in the optimization process of the genetic algorithm, it was still included to show that the produced codebook can be used for various channels. Also, it should be noted that the Ricean Factor κ is set to 1. Figure 6.5 shows the BER performances of the selected Pareto-Codebooks and the ones from the literature. Pareto Codebooks have approximately 1dB gain over Huawei and Klimentyev codebooks, 3dB gain over Vikas codebook, and approximately 1dB loss compared to Li and Huang codebook at 10^{-3} BER. This loss over the Huang codebook is caused by the fact that the only design criterion of this codebook was the AWGN channel and was

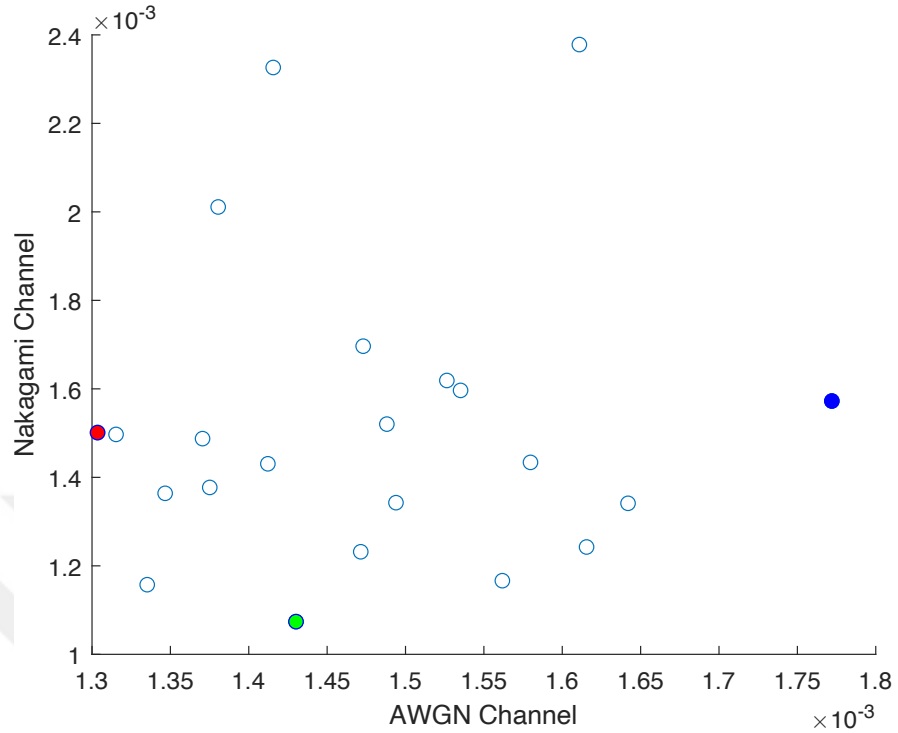


Figure 6.3 BER distribution of AWGN and Nakagami Channels

optimized solely for the AWGN channel, and the loss over the Li codebook results from the fact that they assigned different power levels to the users and thus exploiting near-far effect. In Rayleigh channel, Pareto Codebooks has 5dB gain over the Huang codebook and 3dB gain over Klimentyev codebook, and Pareto Codebooks have 0.3, 0.2 and 0.1dB gain over Li codebook but 1dB loss over Vikas codebook (it should be noted that Vikas codebook exhibits the worst performance in AWGN channel) at 10^{-3} BER. A similar situation is seen at the Ricean channel (which is not unusual since Rayleigh channel is a special case of Ricean channel with no line-of-sight). In Nakagami-2 channel. Pareto Codebook 1 and Pareto Codebook 3 have a slight gain over Li codebook, approximately 1dB gain over Huang codebook and 2dB gain over Vikas and Klimentyev codebook.

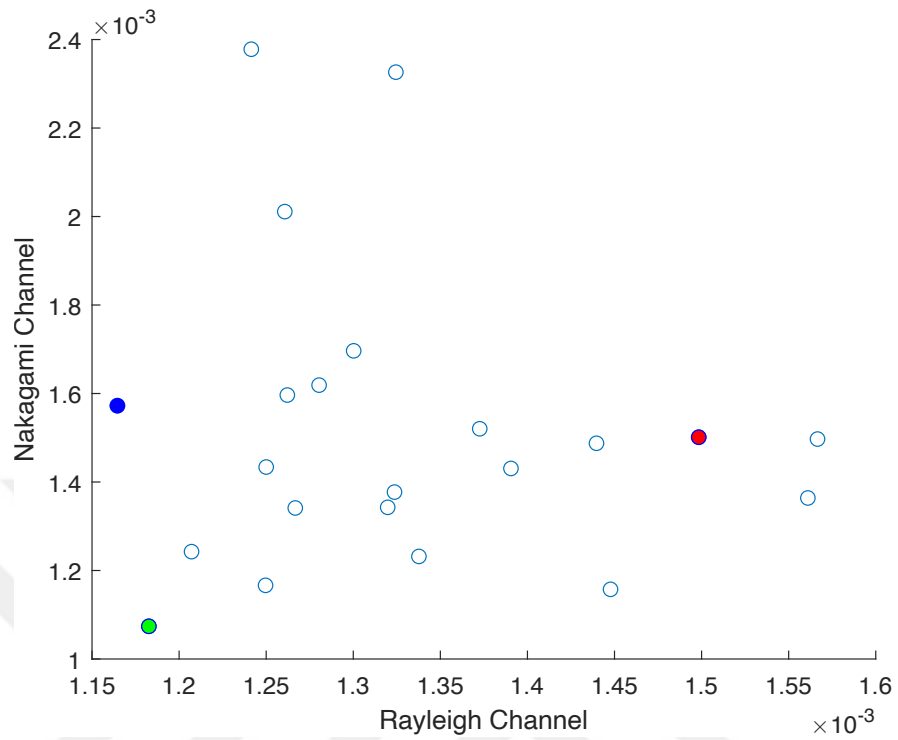


Figure 6.4 BER distribution of Rayleigh and Nakagami Channels

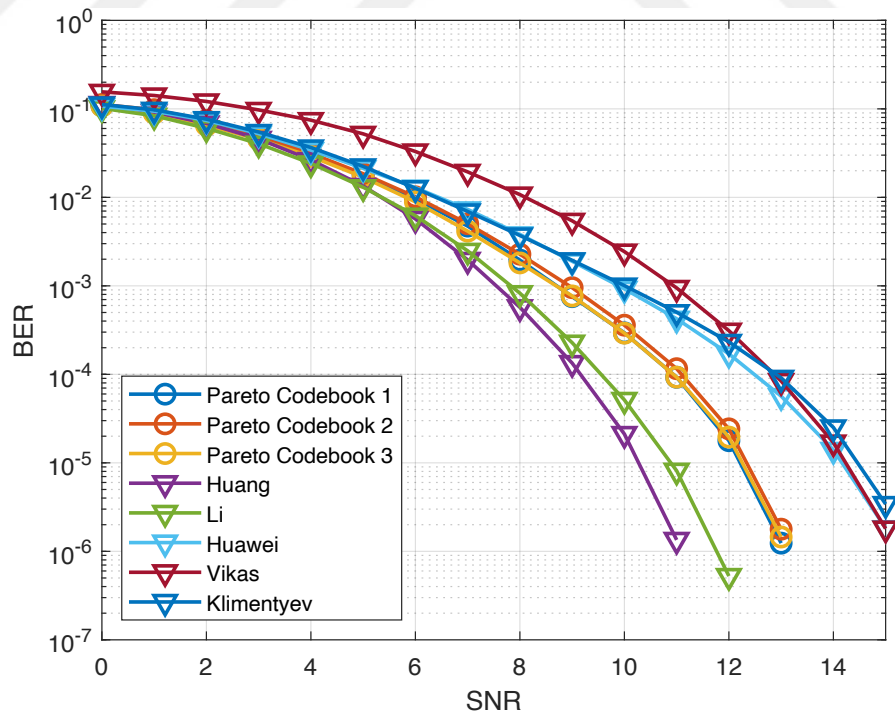


Figure 6.5 Performance Result in AWGN Channel

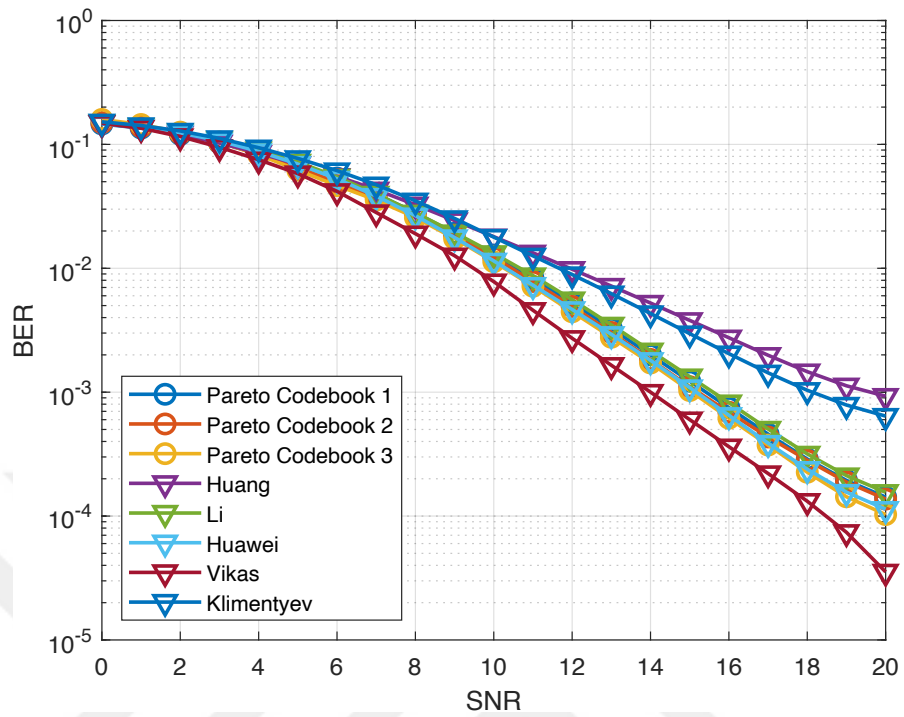


Figure 6.6 Performance Result in Rayleigh Channel

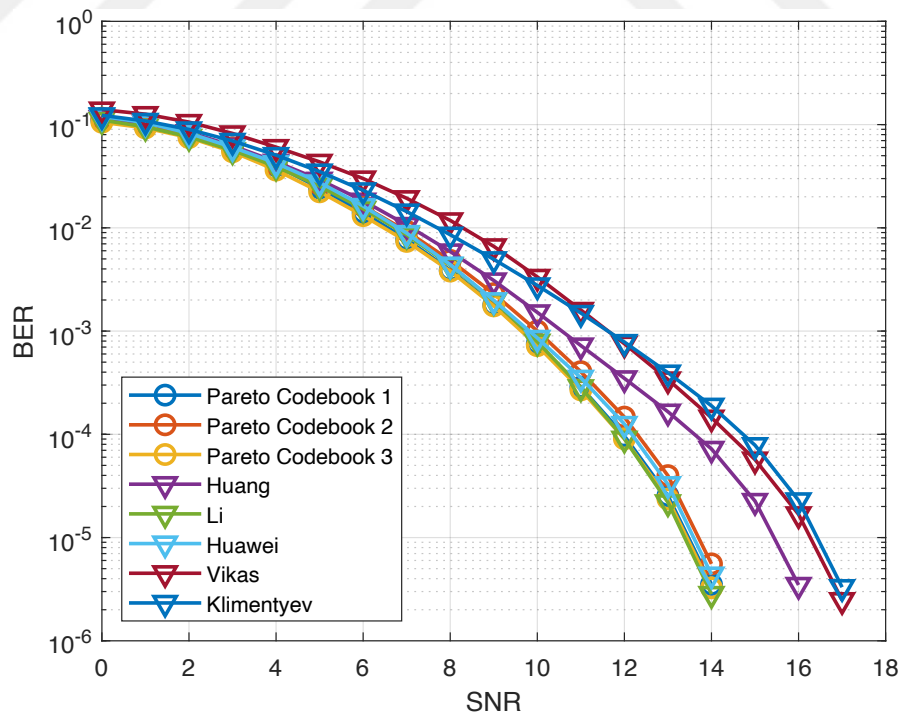


Figure 6.7 Performance Result in Nakagami-2 Channel

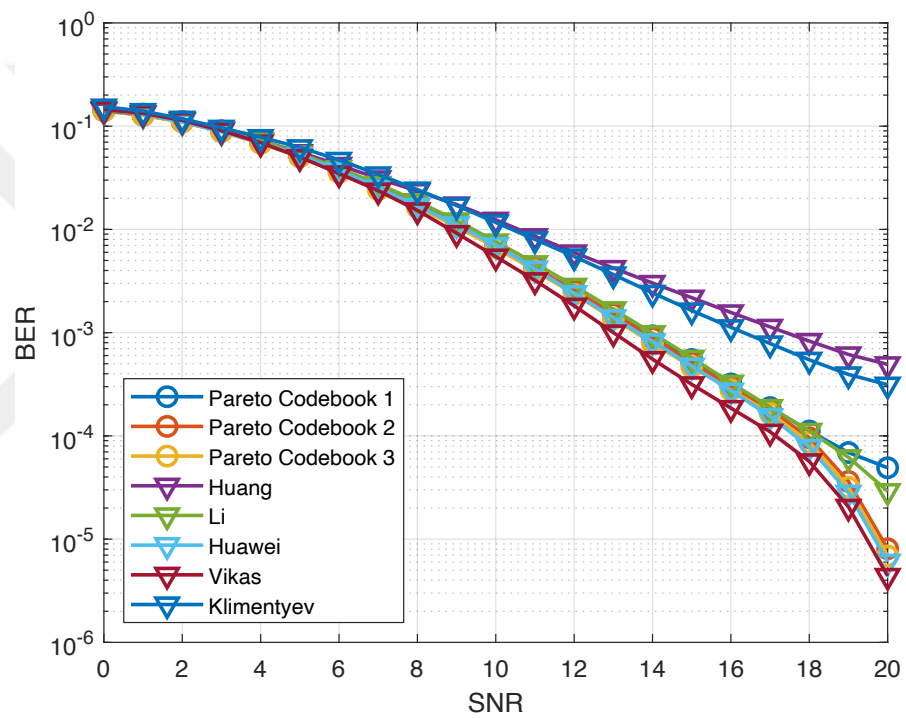


Figure 6.8 Performance Result in Ricean Channel

7. CONCLUSION & FUTURE RESEARCH

In the second chapter, the effect of fast-fading channels with different fading rates over SCMA systems is investigated with the Huawei codebook, and it was found that SCMA systems are highly intolerant to fast-fading scenarios because of this a slightly more time-consuming but highly effective method called HR-MPA is proposed.

In the third chapter, the effect of pilot signals over channel estimated performance of SCMA systems is investigated, and a new method for creating and optimizing non-orthogonal pilots with the help of genetic algorithms is investigated.

In the fourth chapter, the adverse effects of Intersymbol Interference over SCMA systems are shown, and the possible use of PN Sequences and their generations are investigated.

In the fifth chapter, an SPEA-2 and Monte-Carlo simulation-based codebook design is investigated, and it was observed that even though we included different types of channels in the optimization process, a trade-off between channel performances is not avoidable.

In future studies, the addition of new system-level performances aimed to be included, such as turbo coding, spectral efficiency, and more realistic fast-fading scenarios such as Jake's model.

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