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Non-Orthogonal Multiple Access for Machine-Type Communications toward 6G

Author Eemeli Nevalainen

Supervisors Sivalingam Thushan
Dr. Nurul Huda Mahmood
Prof. Nandana Rajatheva

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ABSTRACT

Massive machine-type communications (mMTC) is one of the main focus areas in the fifth generation of wireless communications. It is also the fastest-growing field in terms of the number of devices. The massive increase in devices connected to the internet and global data traffic creates unprecedented requirements for future generations of wireless communications. One of the key technologies for the performance of the system is the utilized multiple access (MA) scheme. The conventional orthogonal MA (OMA) schemes from the earlier generations fail to satisfy the increasing demands for connectivity and spectral efficiency. On the contrary, non-orthogonal MA (NOMA) schemes offer the connectivity and spectral efficiency needed to enable mMTC. NOMA does this by allowing multiple users to transmit their data through the same resource blocks (RBs) simultaneously. NOMA is generally divided into two categories, namely power domain (PD-) NOMA and code domain (CD-) NOMA. PD-NOMA utilizes the power domain for the multiplexing, whereas CD-NOMA uses the code domain. This thesis focuses on the fundamentals of NOMA, MTC, and what NOMA can offer to MTC. We will also discuss the challenges and open problems that need to be solved. Finally, the thesis includes some simulations that demonstrate NOMA in practice.

Keywords: Code domain NOMA, Machine-type communications (MTC), Non-orthogonal multiple access (NOMA), Power domain NOMA.

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TIIVISTELMÄ

Massiivinen kone-tyyppinen kommunikaatio (mMTC) on yksi viidennen sukupolven langattoman viestinnän pääpainopisteistä. Se on myös nopeimmin kasvava osa-alue, kun katsotaan laitteiden lukumäärää. Internetiin yhdistettyjen laitteiden ja globaalin tietoliikenteen valtava kasvu luo ennennäkemättömiä vaatimuksia tuleville langattoman viestinnän sukupolville. Yksi avainteknologioista järjestelmän suorituskyvyn kannalta on käytetty monikäyttömenetelmä (MA). Tavanomaiset ortogonaaliset MA (OMA) -järjestelmät eivät saavuta yhdistettävyyden ja spektritehokkuuden kasvavia vaatimuksia. Sitä vastoin ei-ortogonaaliset MA (NOMA) -järjestelmät tarjoavat mMTC:n mahdollistamiseen tarvitun yhdistettävyyden ja spektritehokkuuden. NOMA saavuttaa tämän sallimalla usean käyttäjän lähettää dataa saman resurssilohkon kautta samanaikaisesti. NOMA voidaan yleisesti jakaa kahteen kategoriaan, tehoalueen NOMA:an ja koodialueen NOMA:an. Tämä työ keskittyy NOMA:n ja MTC:n perusteisiin ja siihen, mitä NOMA voi tarjota MTC-käyttökohteille. Työssä käydään myös läpi ratkaisuja vaativat haasteet ja avoimet ongelmat. Lopuksi työ sisältää simulaatioita, jotka mallintavat NOMA:n toimintaa käytännössä.

Avainsanat: Ei-orthogonaalinen monikäyttö (NOMA), Kone-tyyppinen kommunikaatio (MTC), Koodialue NOMA, Tehoalue NOMA.

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LIST OF ACRONYMS

1G	first generation of wireless communications
2G	second generation of wireless communications
3G	third generation of wireless communications
4G	fourth generation of wireless communications
5G	fifth generation of wireless communications
6G	sixth generation of wireless communications
AWGN	additive white gaussian noise
BER	bit error rate
BPSK	binary phase shift keying
BS	base station
CD	code domain
CDMA	code domain multiple access
CTU	contention transmission unit
FDMA	frequency division multiple access
HD	high definition
HTC	human-type communications
IoE	internet-of-everything
IoT	internet-of-things
LDS	low-density spreading
LLR	log-likelihood ratio
MA	multiple access
mMTC	massive machine-type communications
MPA	message passing algorithm
MTC	machine-type communications
MTD	machine-type device
MUD	multi-user detection
NOMA	non-orthogonal multiple access
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OMA	orthogonal multiple access
PD	power domain
RA	random access
RB	resource block
SC	superposition coding
SCMA	sparse code multiple access
SIC	successive interference cancellation
SMS	short message service
SNR	signal-to-noise ratio
TDMA	time division multiple access

1 INTRODUCTION

In recent years, the number of devices connected to the internet and global data traffic have increased significantly. The monthly data traffic globally is predicted to increase to 607 Exabytes by 2025 and to 5016 Exabytes by 2030. Also, as shown in Fig. 1, the number of connected devices is expected to increase from 18.3 billion in 2018 to 29.2 billion by 2023. The fastest-growing part of the devices is the machine-type devices (MTDs). They are predicted to more than double their quantity from 6.1 billion in 2018 to 14.7 billion by 2023 [1]. This rapid increase forces the wireless communications industry to develop technologies to match the demands.

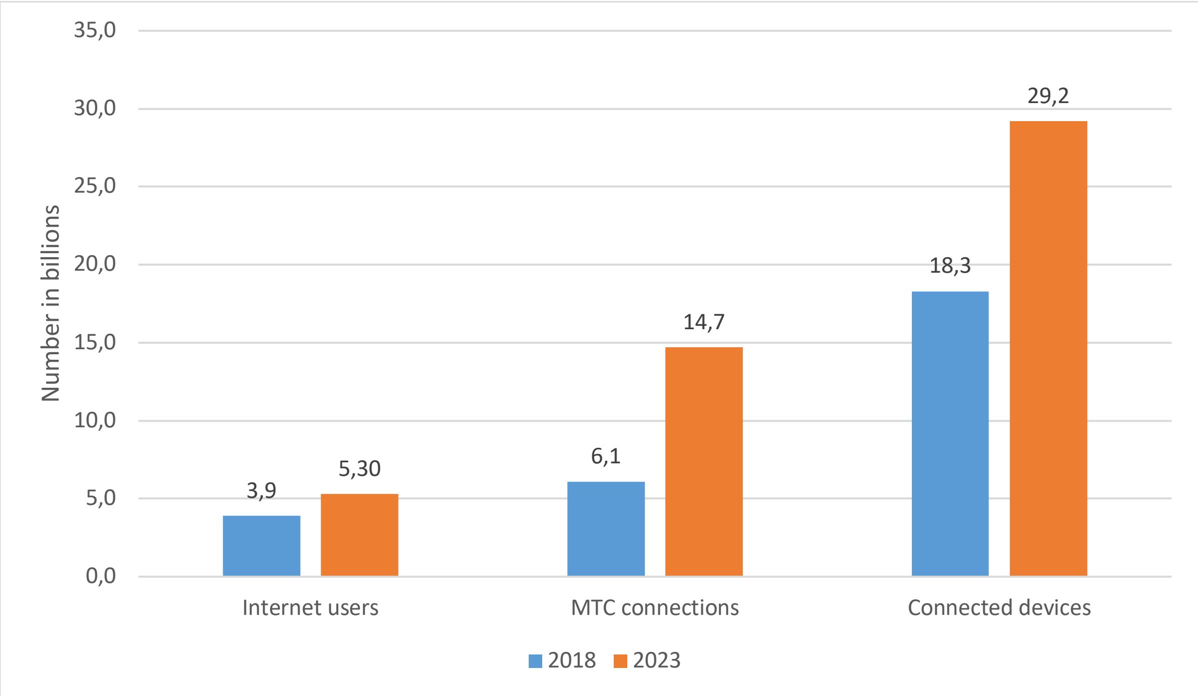

Figure. 1: The number of internet users, machine-type communications (MTC) connections, and connected devices in total [1].

One of the key enabling techniques for wireless communications is the multiple access (MA) technique. MA techniques provide the ability to serve multiple users at the same time. Through the generations of wireless communications, the abilities of MA techniques have evolved considerably. In the first generation (1G), the utilized MA technique was Frequency Division Multiple Access (FDMA). In FDMA, the users are served through user-specific frequency slots. In the 2G GSM system, Time Division Multiple Access (TDMA) was used. In TDMA, the users are divided in the time domain. Code Domain Multiple Access (CDMA) is the most prominent MA technique in 3G networks. Contrary to the earlier generations, CDMA can serve multiple users through the same resource block (RB). It uses user-specific spreading sequences to distinguish the users from each other. In 4G, orthogonal frequency division multiple access (OFDMA) was introduced. In this scheme, the frequency slots are arranged orthogonally. These MA schemes from the earlier generations are commonly categorized as orthogonal MA (OMA) schemes [2].

When it comes to 5G, conventional OMA schemes struggle to satisfy high spectral efficiency and massive connectivity requirements. In OMA schemes, the number of users that can be served is restricted by the number of available orthogonal resources [3]. One of the main parts of 5G is the Internet of Things (IoT), which contributes to the massive increase in the number of MTDs. The limitations of OMA become especially problematic in massive machine-type communications (mMTC), where a vast number of MTDs require service. Furthermore, the upcoming 6G introduces the Internet of Everything (IoE) [1], which will further increase the required connectivity. Therefore, it is necessary to find MA schemes that can outperform conventional OMA schemes.

TABLE I: Evolution of wireless communications from 1G to 5G [1].

Generation	**Time period**	**MA schemes**	**Key features**
1G	1980-1990	FDMA	Analogue voice calls
2G	1990-2000	TDMA	Digital voice calls, short message service (SMS)
3G	2000-2010	CDMA	Voice, data, video calls
4G	2010-2020	OFDMA	Video, fast mobile broadband
5G	2020-2030	NOMA	IoT, ultra high definition (HD)

One possible solution for the problem is non-orthogonal multiple access (NOMA). NOMA can support a significantly larger number of users than OMA since it utilizes non-orthogonal resource allocation. This allows NOMA to use the available resources more efficiently and serve multiple users with different requirements through the same resource blocks [2]. This thesis includes the basics of NOMA, MTC, and how NOMA can be used to facilitate supporting multiple users in MTC. The thesis also contains simulations that support the theoretical part and demonstrates the use of NOMA in practice.

2 THE THEORETICAL BACKGROUND OF NON-ORTHOGONAL MULTIPLE ACCESS AND MACHINE-TYPE COMMUNICATIONS

2.1 Non-Orthogonal Multiple Access

The innovative concept of NOMA is considered one of the key enabling technologies for future generations of wireless communications. The main idea of NOMA is to facilitate supporting multiple users. NOMA allows users to be served simultaneously through the same time/frequency RB. NOMA offers significant advantages compared to conventional OMA schemes of the earlier generations of wireless communication. Since multiple users use the same RB, the spectral efficiency of NOMA is higher than OMA. Furthermore, this enables massive connectivity for MTC purposes. In NOMA, the power is allocated more fairly between users, meaning that the weaker users get more power. Also, NOMA can potentially be integrated with existing multiple access schemes since it utilizes the power domain [2]. NOMA schemes can be divided into two main categories: code-domain NOMA (CD-NOMA) and power-domain NOMA (PD-NOMA).

2.1.1 Power-Domain NOMA

The basic principle behind PD-NOMA is to add a new dimension for multiplexing, namely the power domain. This new dimension unlocks the ability to serve multiple users through the same time/frequency resource block. In PD-NOMA, the available transmission power is divided between users regarding their channel conditions. Generally, PD-NOMA requires asymmetrical channels, namely a near-far situation, to work efficiently. Usually, the user far from the base station (BS) has the worst channel and receives a higher power level than the nearby user. The power difference can be utilized in reception to distinguish different users' signals. The main techniques used in PD-NOMA are superposition coding (SC) at the transmitter and successive interference cancellation (SIC) at the receiver [3].

SC is a non-orthogonal multiplexing scheme used at transmission in the downlink. SC can be utilized when two users have asymmetrical channel conditions. In this case, the user with the better channel can decode the signals of the weaker user. In SC, different users' signals with different channel conditions are superimposed after normal modulation and channel coding [2]–[4]. SC also allocates the transmission power between users. The resulting signal x in a K-user system is

$$x = \sum_{i=1}^{K} \sqrt{p_i} x_i, \tag{1}$$

where p_i is the power allocation and x_i is the signal of user i, respectively, such that the total transmit power is the sum of the individual power allocations, i.e., $\sum_{i=1}^{K} p_i = P$. The authors in [3] show that the performance of the SC scheme is better than the orthogonal schemes. The received signal y_i for user i is

$$y_i = h_i x + \omega_i, \tag{2}$$

where h_i is the channel coefficient and ω_i is the noise from the channel. These superposed signals can be decoded with SIC. SIC is a multi-user detection (MUD) technique that exploits the power difference of the received signals. It iterates through the received signals, and the signals are decoded, demodulated, and subtracted from the combined signal. The ideal iteration order is from the strongest to the weakest signal since the strongest has the least interference. This procedure removes the interference of the superimposed signals leaving only the desired signal [2].

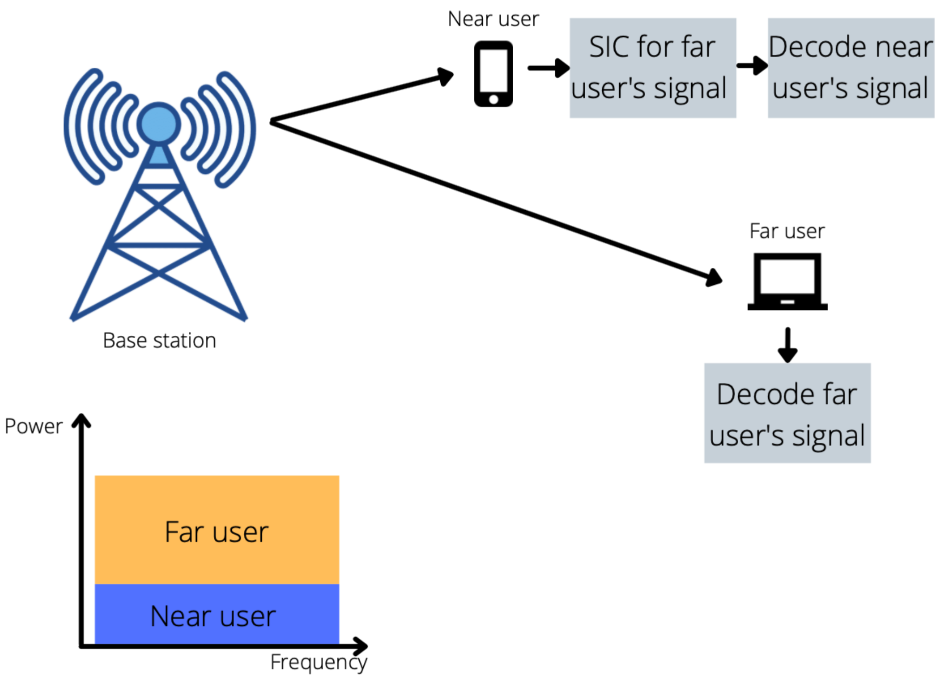

Figure. 2: PD-NOMA in downlink.

In a two-user downlink system, as shown in Fig. 2, the near user uses SIC to decode and cancel out the far user's signal from the combined signal since the far user's signal has more power and therefore dominates the other signal. On the other hand, the far user treats the near user's signal as noise, and it does not need SIC to decode the desired signal. However, as the number of users increases, SIC becomes more challenging to perform, requiring more computational power. Furthermore, the error propagation of SIC can seriously affect the error probability of the system. This behavior can be prevented or at least reduced with advanced user pairing, power allocation methods, and channel coding schemes. However, the complexity of the receiver increases drastically [3].

SC and SIC performed together are superior to conventional OMA schemes. The benefits are especially significant when the users' power difference is substantial, i.e., when the users' distances from the BS are considerably different. Conversely, when the users' power is equally distributed, PD-NOMA does not offer any gain compared to conventional OMA [4]. In the downlink for a two-user system, the boundary of the channel capacity region in the additive white gaussian noise (AWGN) channel can be formulated as [3], [5],

$$R_1 = W \times \log_2(1 + \frac{p_1|h_1|^2}{N_{0,1}W}), \quad (3)$$

$$R_2 = W \times \log_2\left(1 + \frac{p_2|h_2|^2}{N_{0,2}W + p_1|h_2|^2}\right), \quad (4)$$

where W is bandwidth, p_n is the transmitted power, h_n is channel coefficient and N_0 is the power spectral density of Gaussian noise. Fig. 3 shows the channel capacity region comparison for OMA and NOMA in a two-user downlink system. In the (a) case, the users' channel conditions are symmetrical and in the (b) case they are asymmetrical. The channel conditions are modeled by signal-to-noise ratios (SNRs) $p_{total}|h_n^2|/N_0$. In the symmetrical case (a), the SNR ratios are the same and in the asymmetrical case (b), user 1 has an SNR value of 20 dB and user two has 0 dB.

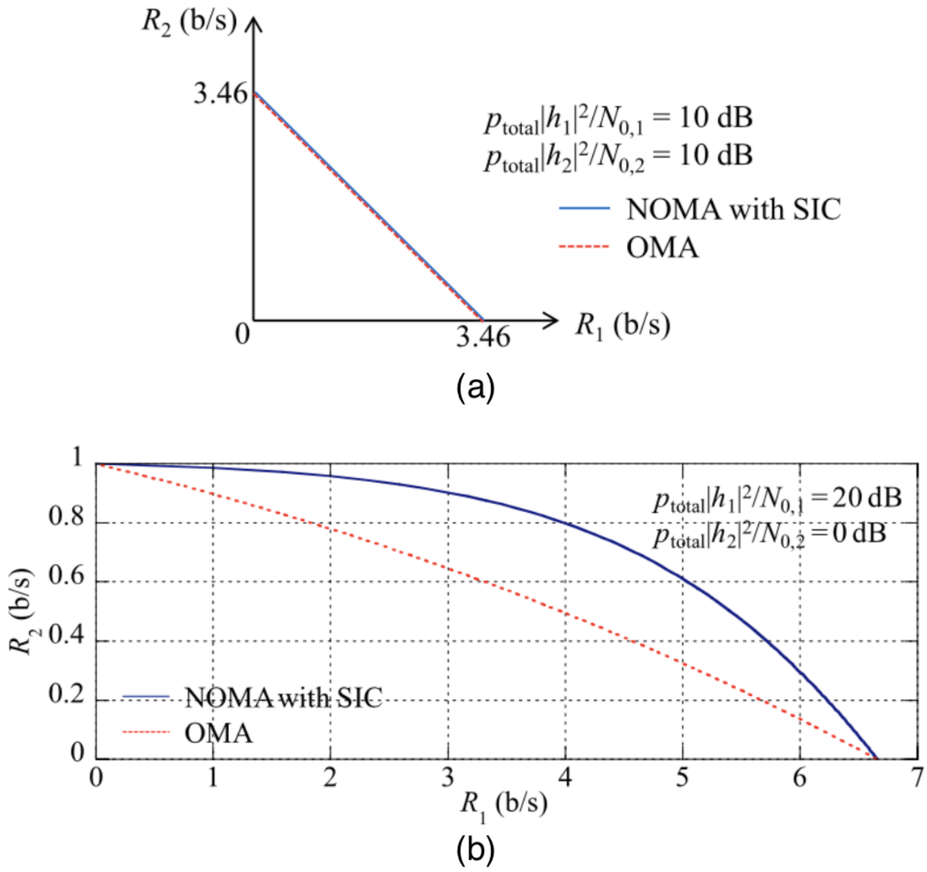

Figure. 3: Two-user system channel capacity regions for OMA and NOMA schemes in downlink AWGN channel and in (a) symmetrical channels and (b) asymmetrical channels [5].

In the asymmetrical case Fig. 2a, the capacity region of NOMA has a larger area than the region of OMA, which means that NOMA has a better channel capacity than OMA. The region is wider since the channel capacity of user one is limited by bandwidth rather than power, and the use of SC allows user one to use the whole bandwidth. In the case of OMA, the bandwidth has to be shared with the two users, and therefore the bandwidth-limited channel capacity decreases [5]. Therefore, PD-NOMA outperforms conventional OMA schemes in terms of rate.

2.1.2 Code-Domain NOMA

In contrast to PD-NOMA, where multiplexing is done in the power domain, CD-NOMA does the multiplexing in the code domain. Different users are allocated different codes. The basic idea of CD-NOMA is inspired by CDMA from 3G systems, where multiple users share the same RBs with spreading sequences unique to each user. The main difference is that in CD-NOMA, the user-specific spreading sequences are sparse sequences or non-orthogonal low cross-correlation sequences. Furthermore, the receiver usually uses MUD techniques based on the message pathing algorithm (MPA). Also, CD-NOMA schemes usually require a larger bandwidth than PD-NOMA [6]. The most prominent CD-NOMA schemes are Low-Density Spreading (LDS)-CDMA, LDS-OFDM, and Sparse Code Multiple Access (SCMA) [3], [7].

The message passing algorithm can simplify the calculation of the marginal probability distribution for random variables $x_1, x_2, \ldots, x_N$ as follows [3]:

$$p(x_n) = \sum_{\sim\{x_n\}} p(x_1, x_2, \ldots, x_N), \tag{5}$$

where $p(x_1, x_2, \ldots, x_N)$ is the joint probability function for the variables, and $\sim\{x_n\}$ represents all the variables except x_n. It is assumed that the joint probability function can be formulated as [3],

$$p(x_1, x_2, \ldots, x_N) = \frac{1}{Z} \prod_{m=1}^{M} f_m(X_m), \tag{6}$$

where Z is a normalized constant, X_m is a subset of $\{ x_1, x_2, \ldots, x_N \}$ and $f_m(X_m)$ is a positive function. This form can be represented as a factor graph as shown in Fig. 4. The MPA generally takes the factor graph representation as an input, and the output is the marginal distribution of all variables. The messages can be passed between the variable and observation nodes through an edge that exists if and only if $x_n \in X_m$. The messages can then be interpreted as soft values that display the reliability of the variables that are associated with the edges. Finally, the marginal distributions of the variables can be represented as functions of the messages that the variable node has received [3].

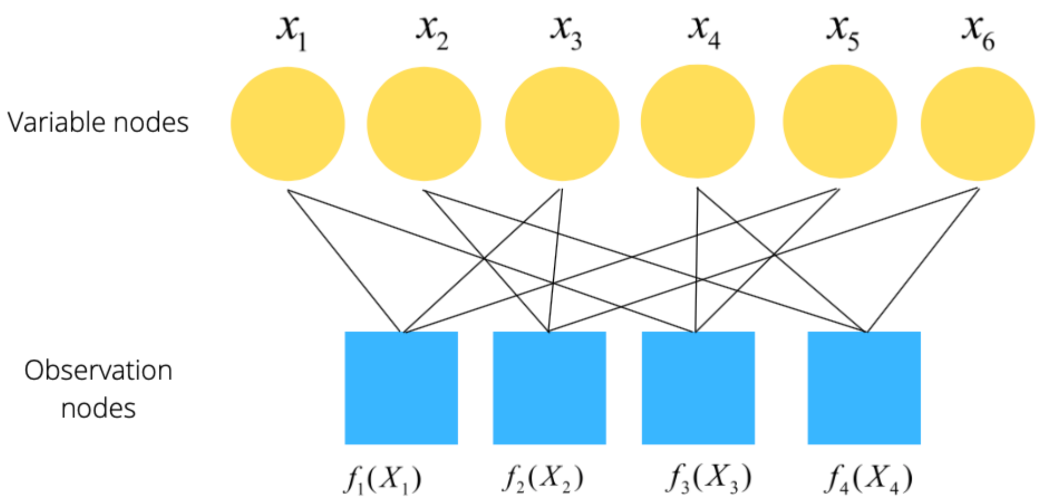

Figure. 4: Factor graph representation of MPA [3].

The LDS-CDMA scheme utilizes sparse spreading sequences that limit interference between users. It is developed from conventional CDMA, but it uses LDS instead of conventional spreading sequences [3], [8]. The LDS spreading process is introduced in Fig. 5. The process consists of spreading, zero-padding and interleaving. First, the users spread their signal across a few chips. Then the spreading sequences go through zero-padding, where the processing gain remains the same. In the final stage, the sequences are interleaved uniquely for each user. This increases the sparsity of the resulting matrixes. In the interleaving process, each chip is assigned a contribution of only a few users instead of all users. Therefore, the interference patterns are unique for each user, and the interference from unused chips can be neglected in detection. The principle of LDS spreading is that if a part of a user's signal is superposed by parts of signals from a moderate number of interferers, the search space should diminish. Therefore, a simpler detection technique can be used. Furthermore, the LDS structure benefits from a natural interference diversity since it avoids interference corrupting all chips of a user [9].

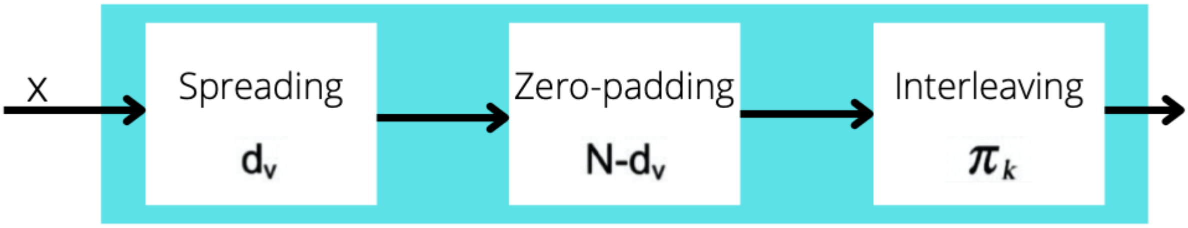

Figure. 5: LDS Spreading process [9].

LDS-OFDM is very similar to LDS-CDMA, but in this case, OFDM modulation is used after spreading. First, the symbols are multiplied by the LDS sequences resulting in chips transmitted on different subcarriers. The LDS sequences' length is equal to the number of subcarriers. Contrary to the conventional OFDMA scheme, where only a single symbol is mapped to each subcarrier, the symbols are spread across a specific fraction of the subcarriers and superimposed in the frequency domain. Consequently, the chips are connected to a part of the original symbols [3].

The SCMA technique is based on the basic LDS-OFDM scheme, but there are some improvements. Contrary to LDS-OFDM, SCMA combines mapping the bitstream and LDS spreading. The bitstream is mapped to sparse codewords of different codebooks generated by a multidimensional constellation. This gives SCMA the coding gains of the constellations, contrary to the repetition code of LDS. Therefore, SCMA has better spectral efficiency than LDS while still benefitting from LDS's overloading and reasonable detection complexity [10]. In the uplink SCMA, unique codebooks are assigned to each user [11]. MPA can be used at the receiver as a MUD technique, but as the number of users and codebooks grows, the complexity can increase drastically [3]. However, in [12], a logarithm-domain MPA (Log-MPA) decoding algorithm with low complexity was proposed. In Log-MPA decoding, most of the multiplication and exponent operations can be turned into basic addition and maximization reducing computation time and complexity in hardware implementation. The decoding complexity was reduced by more than 50%.

2.2 Machine-Type Communications

MTC is one of three service classes introduced in 5G. It is also one of the fastest-growing fields in wireless communications. The number of MTDs increases faster than the number of other devices. MTC has a variety of possible applications, from smart homes to smart transportation systems [6].

MTDs are mostly small devices like sensors and actuators that collect information from the surroundings with little to no human involvement. They can perform tasks including sensing, actuating, storing, communicating, and computing. They can be fixed, mobile or wearable, such as smartwatches or health sensors. MTDs can communicate with the network directly or indirectly. In direct communication, the device utilizes embedded cellular access capabilities to access the network. In indirect communication, on the other hand, the device exploits smartphones via non-cellular communications, such as Wi-Fi or Bluetooth [6].

The characteristics of MTC traffic depend on the application. Most applications are in mMTC, where low-power devices communicate with low data rates since the messages are small. On the other hand, some applications like smart transportation require high data rates or very low latency, as there is no room for error. Generally, the communication traffic in MTC is in the uplink, i.e., from the device to the BS. Also, the nature of MTDs' transmission is sporadic, which requires fast access to the network. The massive number of MTDs increases the probability of collision when many messages come from the same area simultaneously. This can lead to a significant performance bottleneck. Furthermore, the massive number of devices and the different requirements can lead to high signaling overheads [6], [13], [14].

There are some challenges in mMTC that need to be addressed. The massive number of devices require massive connectivity, but the spectrum is limited. Furthermore, MTDs' computational capabilities are low, and their batteries are small since the devices need to be small and cost-efficient. Also, the coexistence with human-type communications (HTC) is challenging because HTC is still the primary field for commercial purposes [6].

2.3 NOMA for MTC

Multiple access techniques are a crucial factor in the network's performance. With conventional OMA schemes, although used efficiently, the limited number of available RBs does not offer connectivity high enough for the requirements of mMTC. Furthermore, the limitations increase the number of collisions, as two users that transmit in the same RB cannot send simultaneously, leading them to collide and re-transmit [14]. Therefore, OMA schemes are not considered sufficient for mMTC. However, as NOMA can serve multiple users through the same orthogonal RB, it is considered an optimal alternative for OMA.

Some of the challenges mMTC are facing could be solved with the adoption of NOMA. Due to the high spectral efficiency of NOMA, it can facilitate supporting the massive number of MTDs in mMTC. Also, NOMA can support multiple MTDs with different data rates or latency requirements with the same RB [15]. Furthermore, NOMA supports the coexistence of HTC and MTC since it allows HTC users and MTDs to share the same resources. NOMA can also be integrated with other techniques to further increase the performance of MTC. For instance, when utilized with beamforming, the available resources can be reused orthogonally between spatially distributed users [6].

Another contributing factor to the system's performance is how devices access the channel resources. The existing wireless network devices request a data transmission slot in the Random Access (RA) process. This process is considered a performance bottleneck in earlier generations of wireless communications, and hence it is not convenient for the required massive connectivity and sporadic nature of mMTC. Instead, grant-free communications would be a more efficient solution for this purpose. In this method, transmissions do not need to go through the RA process reducing signaling overheads and facilitating accessing the network [14]. Instead, the RA request and the message are combined into a single package and transmitted to the BS [6]. However, grant-free transmissions with conventional OMA schemes lead to a large number of collisions due to the limited RBs. On the other hand, with NOMA, the BS can distinguish users from each other based on their unique signature patterns, and hence the collisions can be avoided. In this case, the devices are able to send their messages at any time, which can reduce end-to-end latency and signal overhead. Therefore, grant-free NOMA schemes are considered a suitable solution for the bottleneck [14].

In PD-NOMA for grant-free applications, it is challenging to maintain adequate power level differences among the received signals at the BS without closed-loop power control. Also, PD-NOMA usually requires a distance difference between users to operate efficiently, which makes SIC receiver challenging to implement in grant-free access. On the contrary, some CD-NOMA schemes can generally be customized to support grant-free transmissions. This is done by utilizing a contention transmission unit (CTU), a fundamental building block of a predetermined area in the time-frequency plane for grant-free transmissions. When transmitting data, MTDs randomly choose a unique CTU and send their message accordingly. CTUs facilitate performing efficient MUD in the BS. For example, in a grant-free SCMA scheme, the CTUs can be defined as a combination of time, frequency, SCMA codebook, and a pilot sequence. Now each codebook can be utilized by multiple MTDs, and they can transmit simultaneously. Although different users use the same codebook, the BS can distinguish the messages based on the differing pilot sequences. Therefore, the number of active users could be higher than the number of codebooks, which would be ideal for mMTC.

Although NOMA is promising for mMTC purposes, there are still some problems to solve. One major challenge is finding the NOMA cluster size, i.e., how many users to serve through the same RB. With a larger cluster size, more users are served simultaneously, and hence the available spectrum is used more effectively. However, distinguishing users from each other and decoding their messages becomes more difficult. In the power domain, the users' power level differences decrease. In the code domain, the codebook size increases. Furthermore, performing SIC becomes more complex, and the receiver complexity increases. This becomes a problem, especially in the downlink, as MTDs' computational capabilities are limited. Another open issue is deciding which users should be clustered together to use one RB. The users might differ in channel conditions, requirements or capabilities, and it is difficult to determine which combination of users forms the most efficient cluster [6].

3 SIMULATIONS

3.1 Two-user PD-NOMA

3.1.1 System model

In this section, we investigate the bit error rate (BER) performance of PD-NOMA through numerical simulations to demonstrate its performance in practice. This simulation demonstrates a two-user power-domain NOMA system in downlink over the AWGN channel. We assume that one user is close to the BS, and the other is further away. This means that the channel conditions of the users are asymmetrical. In this case, the power allocation can be done effectively. As a result, we get the two users' BERs. The simulation model was made using MATLAB and Simulink. The Simulink implementation of the system can be seen in Fig. 6. The implementation was made based on [16]. The same simulation model was made with MATLAB code based on [17] to confirm the results.

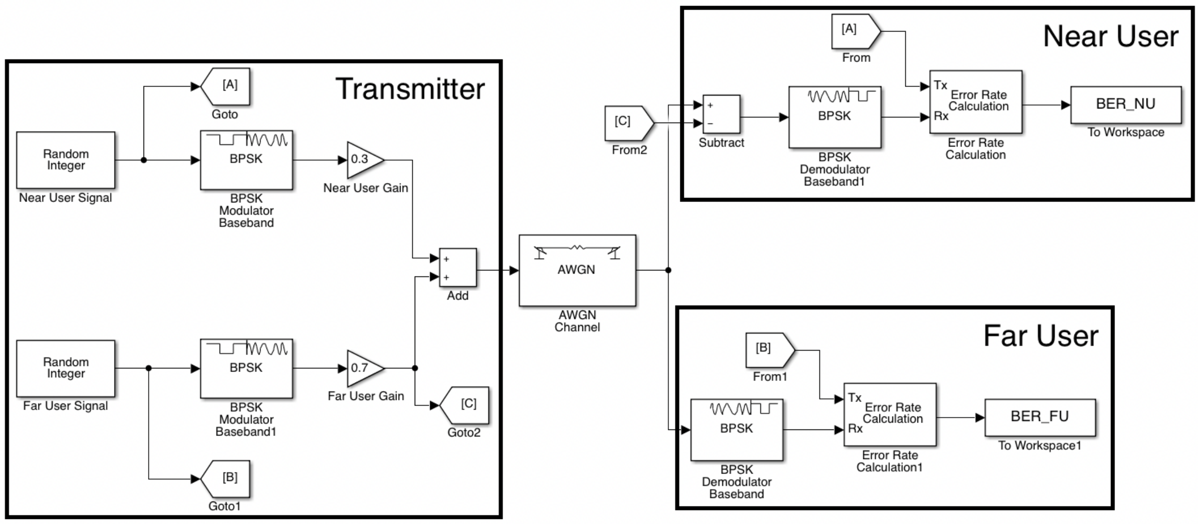

Figure. 6: Simulink model for two-user PD-NOMA [16].

First, the transmitted data is generated for both users in the *Random Integer* -blocks. The *Random Integer* -blocks generate equally distributed integers in the range of [0, M-1], where M is the set size. In this case, M = 2, the created data is in binary form. The data is then modulated using Binary Phase Shift Keying (BPSK). After the modulation, power allocation for the signals is done by multiplying the modulated signals with specific gains, corresponding to multiplying with different power levels [16]. In this scenario, the far user's signal is multiplied by 0.7 and the near user's signal by 0.3. The far user gets more power since its channel is considered worse than the near user's channel. Then the signals are superimposed using SC in the *Add*-block, and the combined signal is transmitted through the AWGN channel. The AWGN channel adds white Gaussian noise to the signal. The initial seed of the channel is 67 and the SNR range is from 0 dB to 18 dB in steps of 3 dB.

On the receiving side, both users receive the superimposed signal. The receivers exploit the power difference of the signals to differentiate them. The near user's signal has less power, and therefore the user must perform SIC to decode its signal. In this model, the near user utilizes perfect SIC, which means that the far user's signal is perfectly known. This is modeled with a direct path for the far user's signal from the transmitter to the near user's receiver. After performing SIC, the resulting signal is the near user's signal with noise from the channel. Then the signal is demodulated, and BER is calculated in the *Error Rate Calculation* -blocks. Finally, the BER data is imported to the MATLAB workspace. Since the near user signal is of low power, the far user can treat it as noise, and hence it does not need SIC to decode its message.

3.1.2 Results

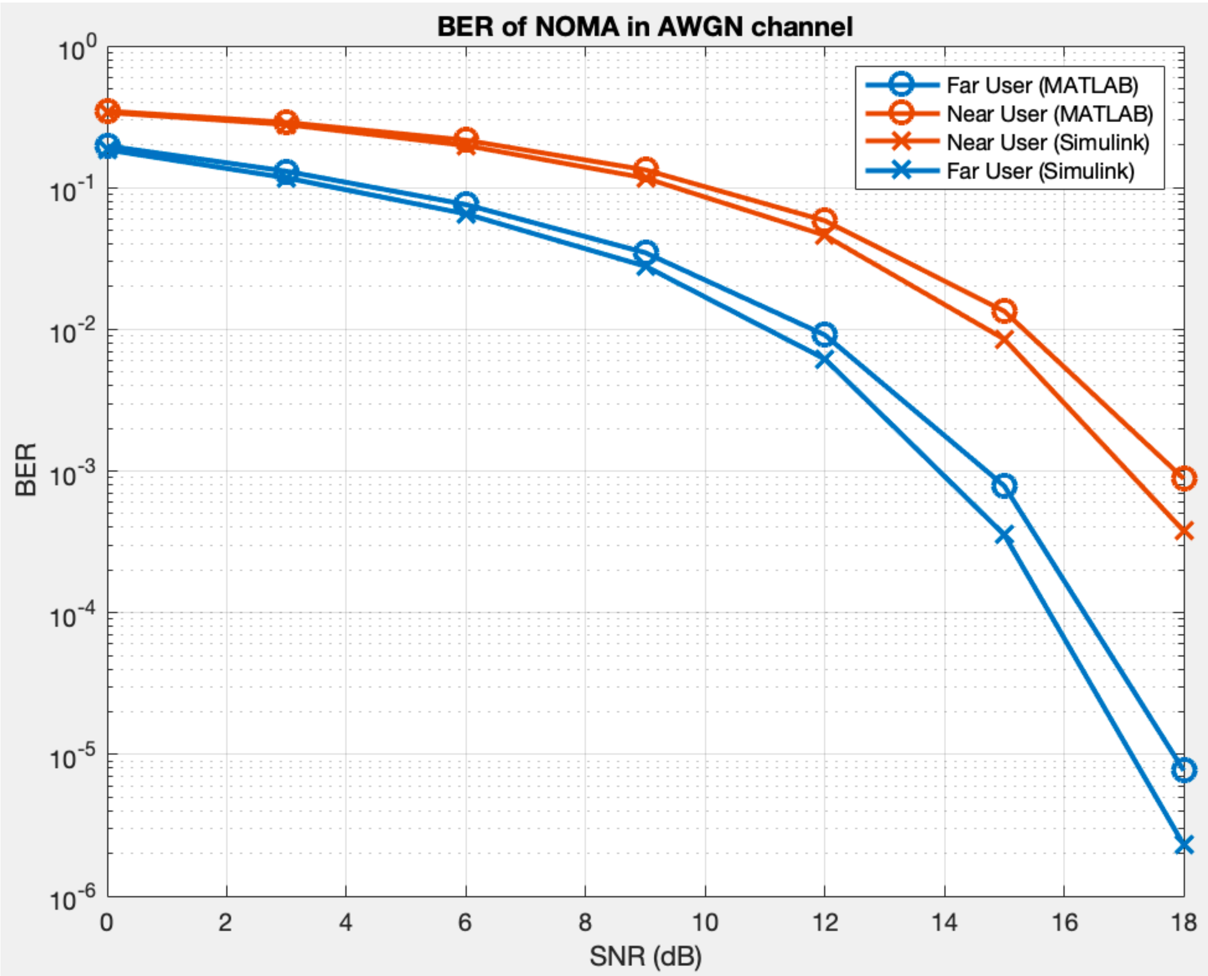

Figure. 7: BER versus the SNR performance of two-user PD-NOMA.

Fig. 7 shows the resulting BER figures of the two users from both simulations. The BER of the near user is higher than the far user. This is because the far user's signal has more power. The interference from the near user's signal combined with the noise from the AWGN-channel has slightly less effect on the far user's signal than the AWGN noise has on the near user. Since the receiver utilizes perfect SIC, it does not affect the BER of the near user.

This model illustrates that PD-NOMA is capable of supporting multiple users through the same resource block. However, the BER values in the simulated SNR range are relatively high and not sufficient for reliable communications. If the figures were extrapolated to higher SNR values, the BER values would eventually decrease to acceptable values. Therefore, the system would need higher SNR values to operate with sufficient reliability.

3.2 SCMA

3.2.1 System model

This simulation model demonstrates the use of SCMA in a six-user system. As a result, we get the BER values of the system. The MATLAB code for the simulation can be found in [18]. Fig. 8 illustrates the system's encoding and multiplexing process. In SCMA encoding, bit-to-constellation mapping and spreading are naturally integrated. In this model, each of the six users has a unique codebook that has four codewords with the length of four and two non-zero elements. The positions of the non-zero elements are unique for each codebook to avoid collisions between users. In this model, the number of codebooks is higher than the length of the codewords, which means that the scenario is rank-deficient. In this scenario, the system is capable of supporting massive connectivity. Each complex codeword is mapped with $log_2 M$ bits, where M is the number of codewords in a codebook. After the randomly generated bitstream is mapped to codewords, the codewords are multiplexed into orthogonal resources like OFDM subcarriers. The number of these resources is the same as the length of the codewords [3].

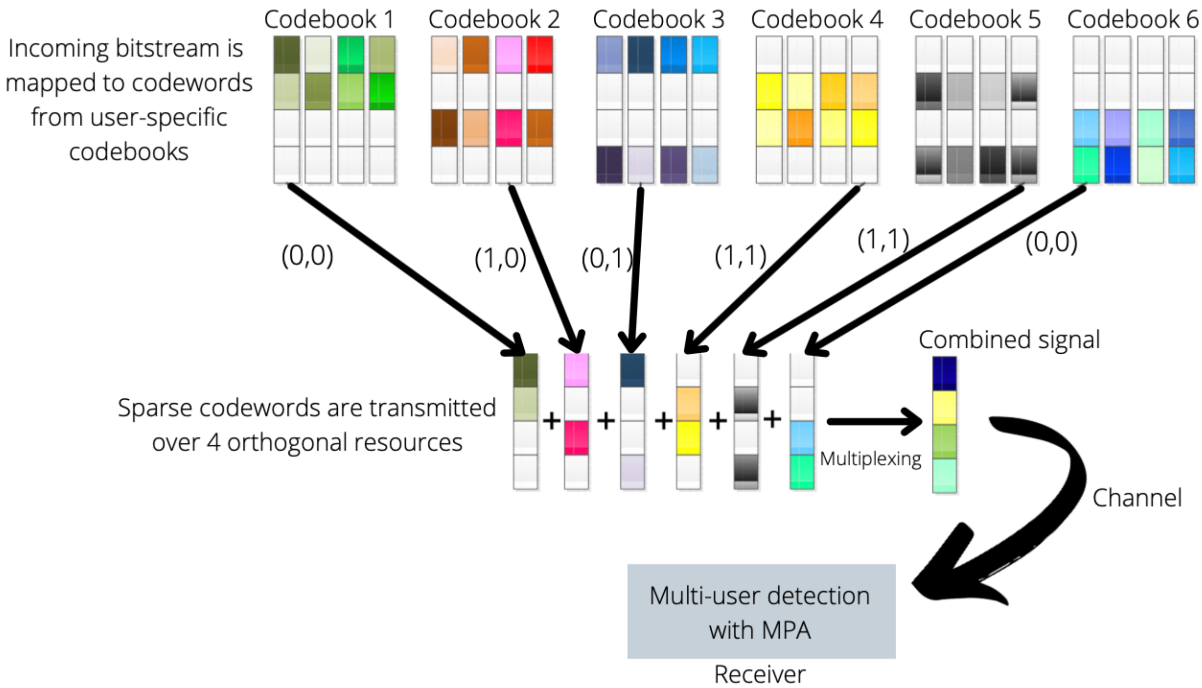

Figure. 8: SCMA encoding and multiplexing [3], [18].

After SCMA encoding and multiplexing, the resulting combined signal is sent over the Rayleigh fading channel to the receiver. The receiver performs SCMA decoding with the Log-MPA MUD technique. The output of the decoder is the Log-Likelihood Ratio (LLR) of the received signal. The LLR value is then converted to bits. Finally, BER is calculated, and the curves are plotted.

3.2.2 Results

As a result of the simulation, we get the BER values of the six users with different SNR values. The BER figures were plotted separately from the simulation.

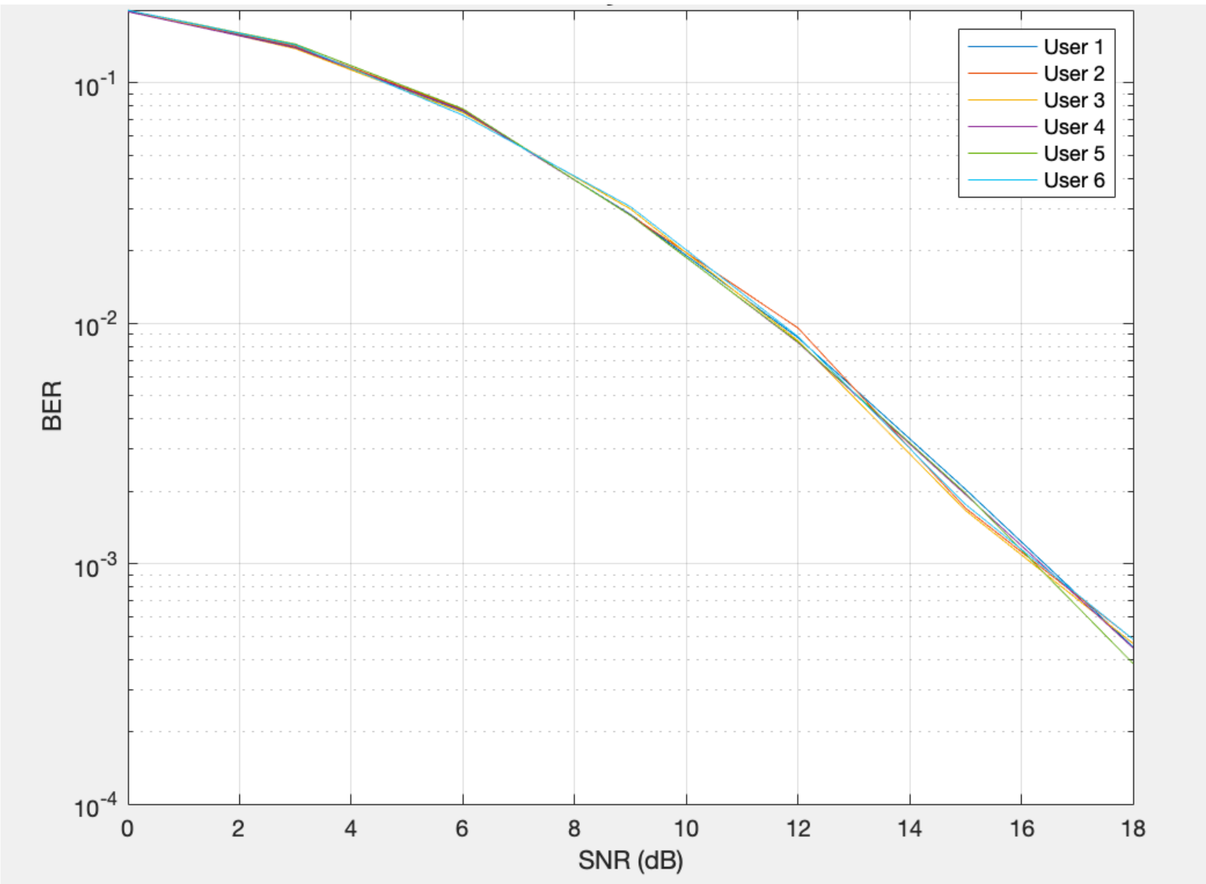

Figure. 9: BER versus the SNR performance for six SCMA users.

The BER figures of each user fit in the same curve, as seen in Fig. 9. The results show that SCMA is capable of supporting more users than the number of available resources. In this scenario, the six users were served over four orthogonal resources, and the users are still able to achieve similar BER performance. In a conventional OMA system, only four users could have been served. Therefore, the modeled system can achieve a normalized user load of 150%. Hence the SCMA scheme can achieve the demanded massive connectivity of mMTC.

4 SUMMARY AND CONCLUSION

This thesis work was carried out from February 2022 to May 2022. The work involved theoretical study to understand the basic concepts of NOMA, MTC, and the use of these technologies together. Then some concepts were simulated using MATLAB and its Simulink environment. The first simulation, a two-user PD-NOMA system, demonstrates a simple NOMA system. This simulation model is a good starting point in understanding the operation of NOMA in practice. The second simulation, a six-user SCMA system, is more complex. This model was selected for the work to extend the knowledge of NOMA schemes in practice.

In this thesis, the fundamentals of the concept of non-orthogonal multiple access have been discussed. Also, the basic characteristics of machine-type communications have been introduced, and how NOMA can be used to improve the performance of MTC systems. Finally, the thesis has included simulations to support the theoretical part and to provide examples of NOMA schemes in practice. This thesis has been made based on existing literature.

In the theoretical part, the basic concept of NOMA has been introduced first. We then have discussed the two main areas of NOMA, namely PD-NOMA and CD-NOMA. The key enabling techniques for PD-NOMA, namely SC and SIC, have been discussed. It has also been proven that these techniques together are superior to conventional OMA schemes. Then the most prominent CD-NOMA schemes have been introduced. After the theory of NOMA, we have discussed the concept of MTC and its characteristic features and challenges. Finally, the benefits and challenges of NOMA for MTC purposes have been discussed.

The simulation part has included two simulations of NOMA systems. The first simulation is a two-user PD-NOMA system, and the model has been made with Simulink and MATLAB. The second model is a six-user SCMA system simulated with MATLAB code. In both simulations, the systems can support multiple users through the same resources and hence provide the connectivity and spectral efficiency that were discussed in the theoretical part.

The concept of NOMA is very innovative, and it is a very promising technique for future generations of wireless communications. There are still open issues that need to be solved, such as determining the NOMA cluster size. However, NOMA could be a key enabling factor for mMTC, especially with grant-free transmissions.

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