BER Analysis on Precoded MIMO-GFDM as Preliminary Study of Waveform Candidates in the Railway Environment

Dara Aulia Feryando[1*], Agustinus Prasetyo Edy Wibowo[1], and Santi Triwijaya[1]

[1]Railway Electrical Technology Study Program, Indonesian Railway Polytechnic,
Madiun 63129, Indonesia
`dara@ppi.ac.id`

Abstract. The high demand for rail transportation services has encouraged the development of research in the field of railways. In the operation of trains, telecommunications has a vital function because it is related to passenger safety. The high speed of train operation requires a telecommunication system that has a high transmission capability of up to Gbps units. Meanwhile, GSM-R technology still has a peak data rate of 172 Kbps while LTE-R still has a peak data rate of 20 Mbps. Therefore, in this study, the use of alternative waveforms in the railway environment is discussed. This study discusses the analysis of the precoded MIMO-GFDM system based on BER parameters. GFDM (Generalized Frequency Division Multiplexing) is one of the waveforms that has been proposed as a candidate for 5G communication. Meanwhile, the use of MIMO in GFDM systems aims to maintain system performance in dealing with multipath channels. The results obtained are that the Precoded MIMO-GFDM system has the same bit error rate when compared to MIMO-OFDM and the Precoded MIMO-GFDM system has optimal results when using 16 subcarriers and 32 subsymbols.

Keywords: BER, GFDM, MIMO, Railway.

1 Introduction

In the railway system, the telecommunications subsystem is one of the subsystems that has a vital function in train operations. The high speed of trains compared to other land transportation requires a telecommunications system on the railway that has a higher transmission speed. In fact, on high-speed trains (HST), the data transmission speed of the telecommunications system is expected to reach the Gbps level. Meanwhile, GSM-R and LTE-R currently used on railways have peak data rates of 172 Kbps and 20 Mbps, respectively [1]. Thus, several researches on techniques to increase data transmission speed on railways have been proposed [2].

Many techniques can be used to increase data transmission speed. One of these techniques is the multicarrier technique [3]. When using multicarrier techniques, the data transmission process involves several subcarrier waves. The use of several subcarrier waves aims to overcome the problem of transmitting signals that have high data rates on multipath channels. The multicarrier technique makes symbols that have broadband characteristics into symbols that have narrowband characteristics. So, when

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symbols are transmitted, it is as if the characteristics of the transmission channel which was previously a frequency-selective fading channel changed to a flat fading channel. In this way, the problem of Inter Symbol Interference (ISI) due to frequency selective fading channels can be resolved [4].

The multicarrier technique has been used in the LTE-R system [5], namely Orthogonal Frequency Division Multiplexing (OFDM), where data is transmitted using several subcarrier waves that have orthogonal properties between one wave and another. However, several studies state that the use of multicarrier techniques in OFDM can increase the Peak Average Power Ratio (PAPR) and Out-of-band (OOB) values of the transmitted signal [6][7]. Meanwhile, in the development of technology towards the fifth generation, several multicarrier techniques using non-orthogonal waveforms have been widely studied and proposed as fifth-generation waveform candidates. There were four non-orthogonal waveforms proposed as fifth-generation waveform candidates at that time [8], namely Generalized Frequency Division Multiplexing (GFDM), Filter Bank Multi-Carrier (FBMC), Universal Filtered Multi-Carrier (UFMC), and Bi-orthogonal Frequency Division Multiplexing (BFDM).

Based on previous research, there are several studies that have discussed the use of non-orthogonal waveform techniques for railway environments. One of these studies is research conducted by Michel Saideh et al, which discusses 5G Waveform for Railway [2]. In the research, it was explained that the main problem of multicarrier in high-mobility environments is Carrier Frequency Offset (CFO). In the 4G LTE OFDM, CFO causes the loss of orthogonality of the OFDM subcarriers between its badly localized subcarriers. On the other hand, studies regarding CFO immunity to non-orthogonal waveforms have been carried out. Non-orthogonal waveforms can minimize CFO with the use of filters, such as using the TFL1 filter in the FBMC-QAM system [9], the root-raised cosine (RRC) filter in the GFDM system [10], and the squared root-raised cosine filter in the FBMC-OQAM system [11].

Apart from CFO, another problem that needs to be considered when using multicarrier techniques is Inter Carrier Interference (ICI). In previous research, modulation techniques, such as OQAM (Offset Quadrature Amplitude Modulation), were used to overcome the ICI problem [12]. OQAM is a modulation technique developed from QAM modulation for nonrectangular pulses. QAM is developed by offsetting or shifting the phase of the QAM quadrature component by T/2, where T is the period of the QAM symbol. Meanwhile, the in-phase component of the QAM signal is left constant. The phase shift in the quadrature component of the signal aims to maintain the orthogonality of the signal using non-rectangular pulses.

In this research, the performance of GFDM which applies RRC and OQAM filters will be analyzed comparatively with the performance of OFDM used in LTE-R, which uses QAM. The analysis is carried out comparatively because GFDM can be considered as a generalization of OFDM [13], which adopts several of OFDM's advantages and has several advantages that can complement OFDM's limitations. Some of the advantages of GFDM are flexibility in setting the formation of symbols, efficiency in bandwidth usage compared to OFDM, and compatibility with Multiple Input Multiple Output (MIMO) techniques [13][14]. Implementing MIMO in GFDM is as simple as implementing MIMO in OFDM because GFDM can be considered a generalization of OFDM. The ease of implementing MIMO is an important point of a 5G waveform candidate because MIMO is one of the features of 5G technology [1].

At the current LTE physical layer, the multicarrier OFDM technique is used in the downlink transmission scheme and SC-FDM for the uplink transmission scheme [15]. The use of different transmission schemes is due to power usage considerations. On the user side, power usage must be managed as efficiently as possible. Therefore, singlecarrier techniques which require lower power than multicarrier techniques are used. On the other hand, multicarrier techniques can be used on the BS side because higher power requirements for high-speed data transmission can be met. The use of multicarrier techniques in the 4G downlink scheme is one of the considerations in this research. Because GFDM is a multicarrier scheme, in this research, both OFDM and GFDM will be applied to the downlink system scheme. The downlink scheme that will be created is a downlink scheme for multiusers or the users in this case are trains connected to the BS.

In the multiuser MIMO downlink communication scheme, Inter User Interference (IUI) is the main problem that needs to be considered [16]. IUI can be resolved if the transmitter knows the channel conditions of each user. The channel conditions of each user can be known by using precoding techniques. In general, precoding techniques are classified into two, namely linear precoding and non-linear precoding. Between the two precoding, linear precoding was chosen because linear precoding has lower system complexity compared to non-linear precoding. There are several linear precoding techniques, namely Channel Inversion (CI), Regularized Channel Inversion (RCI), and Block Diagonalization (BD). Among the three types of linear precoding, the RCI precoding technique was chosen because it can reduce the influence of IUI without causing noise enhancement [17]. In RCI, noise enhancement can be prevented because RCI utilizes the Minimum Mean Square Error (MMSE) criterion.

Based on some of the background presented above, a multiuser GFDM system scheme that applies RRC filters, OQAM mappers, MIMO, and precoding will be analyzed in this research as an initial study of new waveform candidates for the railway environment. System performance will be analyzed based on the bit error rate (BER) parameter. There are two BER analyzes that will be carried out, BER analysis internally to the system and BER analysis externally to the system. Internal BER analysis of the system is divided into two scenarios, the first scenario is to compare the BER of the GFDM system with the BER curve for 16-QAM. Meanwhile, the second scenario is to compare the BER of GFDM systems that use different settings for the number of subsymbols and subcarriers. For external BER analysis, the analysis is carried out by comparing the GFDM system with the OFDM system.

2 Research Methodology

2.1 Flowchart of Research Methods

In general, the research methods that have been carried out can be explained through the flowchart in Figure 1. Literature studies are conducted to find out the latest issues about railways and find solutions to overcome these issues. Some issues that have been identified through literature studies are: 1) Demand for rail transportation services in several countries has increased, including in Indonesia [18]; 2) Wireless technology used in railways has not been able to reach the transmission speed at the Gbps level [1]; 3) Guarantees for product and service support for GSM-R only up to 2030. So, after that time, the railroad sector must be prepared to anticipate risks related to this matter [19]; 4) Some alternative communication systems for future railways are widely studied [1][2][19]; 5) Generalized Frequency Division Multiplexing (GFDM) is one of the non-orthogonal waveform candidates for 5G because GFDM is able to transmit data with speeds up to Gbps level [12][13][20].

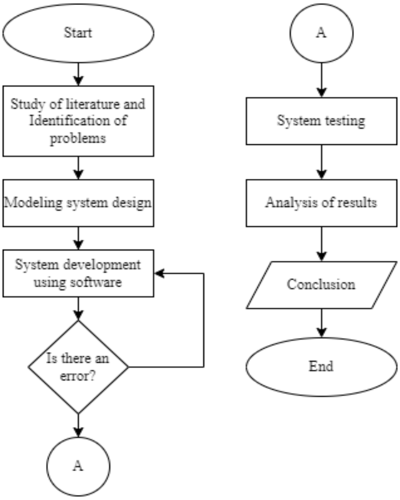

Fig. 1. Flowchart of research methods

Once these issues were identified, potential techniques for improving the performance of telecommunication systems on railways were studied. From this process, several things were obtained: 1) The use of multicarrier techniques can increase data transmission speed and overcome transmission problems on selective fading channels [3]; 2) GFDM, a multicarrier technique that produces non-orthogonal waveforms, is one of the candidate waveforms for 5G because of its ability to increase data transmission speed and its ease in implementing 5G features [18]; 3) Using the RRC filter can minimize CFO [2]; 3) The use of OQAM can overcome ICI between subcarriers [12]; 4) The use of precoding can overcome IUI problems in multiuser downlink communication schemes [16].

The data from the literature study was then collected and used to design communication system modeling. The system model was built using Matlab. Before the system model is tested, the system model is verified to determine whether there are errors in programming. After the system model is verified to be free from errors, system testing is carried out to determine system performance based on BER parameters.

2.2 System Model

In this session, the Precoded MIMO-GFDM system model will be described. The system block diagram is shown in Figure 2.

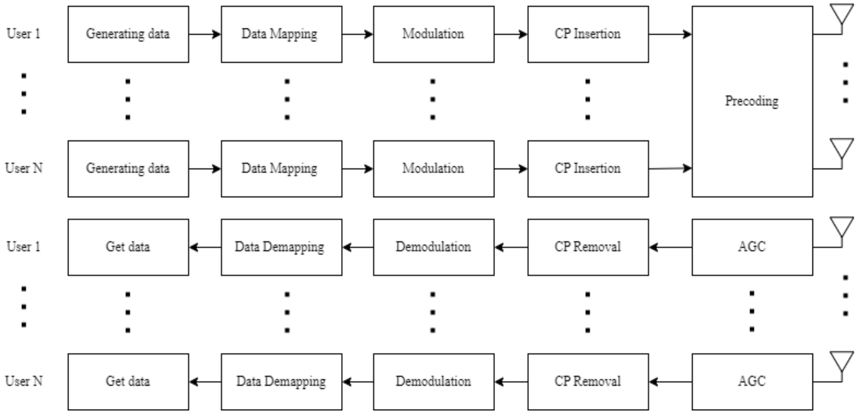

Fig. 2. Transceiver model of the generated system

Data generation is carried out for each u^{th} user. The number of all users is denoted by *N*, where *N* in this study was determined to be 4 users. The amount of data generated for all users in this study follows Monte Carlo simulation. Meanwhile, the length of data generated for each user is assumed to be the same. N_T denotes the number of transmit antennas employed at the base station, where N_T is set to 4. The multiuser scheme proposed in this research assumes that each receiving antenna is a user with a single antenna. Therefore, on the user side, each user uses one receiving antenna. Then, the number of antennas used by all users is denoted by N_R, so N_R is $\sum_{u=1}^{N} 1$.

After data for each user is generated, the data is mapped using 16-OQAM. 16-*ary* was chosen because OFDM on LTE-R uses 16-*ary* QAM. Thus, the OFDM system that was also developed in this research uses a 16-QAM mapping scheme. OQAM is a modulation technique developed from QAM modulation for the use of nonrectangular pulses. QAM is developed by offset or shifting the phase of the QAM quadrature component by $\frac{T}{2}$, where T is the period of the QAM symbol. So, the data bit stream from each user is mapped using QAM techniques first. After that, the quadrature component of the mapping results is shifted by $\frac{T}{2}$. Meanwhile, the inphase component of the QAM signal is left constant.

Next, the mapped data series is processed into a modulator block. In the GFDM modulator block, there are three subblocks, namely the serial-to-parallel subblock, circular convolution subblock, and pulse formation subblock. The data stream originating from the mapper block is converted into a series of data that has a lower data rate in a serial-to-parallel block. Parallel data is decomposed into a GFDM block of size $K \times M$, where K and M denote the number of subcarriers and subsymbols used, respectively. The total elements in a GFDM block are denoted as N_{GFDM}. The results of the decomposition process are then converted into a matrix of size $K \times 1$.

The element of the u^{th} user block data is up-sampled to convert them into impulse signal sequences. After a series of impulse signals are obtained, the signals are shifted circularly and processed in the pulse-shaping subblock. The processes that occur in the circular filter and pulse shaping subblock follow the following equation:

$$g_{k,m}[n] = g[(n - mK) mod N_{GFDM}] exp\left(-j2\pi \frac{k}{K} n\right) \quad (1)$$

n in the equation above denotes the sampling index. Each $g_{k,m}[n]$ is a version of the $g[n]$ filter prototype that has been circularly shifted in terms of time and frequency. The used pulse shape, $g[n]$, in this research is root-raised cosine (RRC). The roll-of-factor (α) value set on the RRC filter in the Precoded MIMO-GFDM system is 1. After the signals go through the pulse shaping process, the signals are then multiplexed so that they become one GFDM block signal. After getting the GFDM block signal, a cyclic prefix (CP) with the size N_{CP} is added. The GFDM signal is obtained from the sum of the GFDM blocks.

In a multiuser downlink scheme, inter-user interference (IUI) can be prevented or minimized if channel state information (CSI) is known. There are two techniques for finding out CSI, namely modal decomposition and pre-equalizer. The RCI precoding used in this research is one of the pre-equalizer techniques. RCI, which works based on MMSE criteria, can overcome IUI without causing noise enhancement. The precoding matrix is generated by following equation 2 below.

$$W = H_s^H (H_s H_s^H + \sigma_z^2 I)^{-1} \quad (2)$$

Where W is the precoding matrix, H_s is the channel matrix of users of size $N_R \times N_T$, σ_z^2 is noise variance of the channel, and $\mathbf{I}$ is an identity matrix of size $N_R \times N_R$. The precoding matrix is then multiplied by the vector data matrix per user that comes out of the CP insertion block to get the precoded GFDM signal. In the final stage of the transmitter system, the GFDM precoded signal is normalized by normalization gain, γ.

$$\gamma = \sqrt{\frac{N_T}{tr(WW^H)}} \quad (3)$$

The channel model from BS to the u^{th} user, or H_u, is complex random numbers with size of $1 \times N_T$. Before the signal is received by the receiver, AWGN noise is added for all user systems. At each receiver, the signal is denormalized in an automatic gain control (AGC) to eliminate the influence of normalization gain. The denormalized signal is demodulated and demapped to obtain the desired information. From the received data, the bit error rate (BER) is calculated. In general, BER is calculated by following equation 4 [19]. Then, the BER of the generated system will be compared with the BER curve for the theoretical 16-QAM scheme. The BER curve for the 16-QAM scheme is generated by following equation 5. In equation 5, the BER formula is written in the form of probability of error [20], where *erfc* is the complementary error function.

$$BER = \frac{total\ bit\ errors}{total\ bits\ sent} \quad (4)$$

$$BER_{16-QAM} = \frac{3}{4} \frac{erfc(\sqrt{2E_b/10})}{2} \quad (5)$$

3 Results and Discussion

As stated in section 1, the performance of the precoded MIMO-GFDM system will be assessed based on the analysis results of the BER parameters. The BER analysis carried out is divided into three scenarios. In the first scenario, BER analysis is carried out by comparing the performance of the precoded GFDM system using the 16-OQAM mapping scheme to the BER curve for the 16-QAM mapping scheme. In the second scenario, BER analysis is carried out by comparing the performance of the precoded GFDM systems with different K and M parameter settings, where $K = 8, 16$ and $M = 8, 16, 32$. The third scenario, BER analysis is carried out by comparing the performance of the precoded GFDM-OQAM system to the precoded OFDM-QAM system. The results of the BER curve are presented in the relationship of $\frac{E_b}{N_0}$ (dB) with BER (dB).

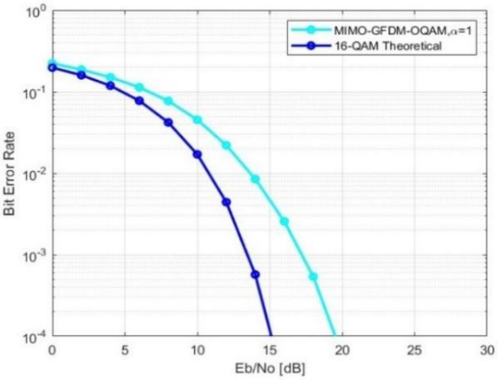

Fig. 3. Comparison of BER curves for the first scenario

The performance comparison results between the GFDM-OQAM system and the BER for the 16-QAM scheme are presented in Figure 3. Based on the results, the performance comparison between the proposed system and the theoretical BER for the 16-QAM scheme is 0.0132 or -18 dB. This means that the Precoded MIMO-GFDM system requires more power (4 dB) compared to the system power that should be achieved.

In the second test scenario, the performance of precoded MIMO-GFDM will be seen based on the use of different K and M values. There are three precoded MIMO-GFDM systems generated. The values of the K and M variables applied to the first precoded MIMO-GFDM system are K = 8 and M = 8. The values of the K and M variables applied to the second precoded MIMO-GFDM system are K = 8 and M = 16. The values of the K and M variables applied to the third precoded MIMO-GFDM system are K = 16 and M = 32. The comparison results of the three systems are shown in Figure 4 below.

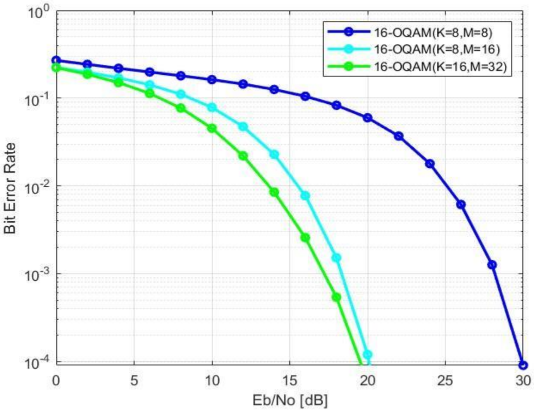

Fig. 4. Comparison of BER curves for the second scenario

Based on Figure 4, the smaller the number of K and M or the GFDM block settings, the greater the probability of bit errors. Conversely, the larger the block size used, the smaller the probability of bit errors. This is because the smaller the block size used, the greater the number of blocks sent. The greater the number of blocks sent causes more independent blocks to be disturbed by noise. Conversely, the larger the block used, the fewer the number of GFDM blocks sent. So, the noise that disturbs the independent block is also lower. In Figure 4, the performance of the precoded MIMO-GFDM system shows the best results when using $K = 16$ and $M = 32$.

In the third test scenario, the BER performance of the precoded MIMO-GFDM system will be compared to the precoded MIMO-OFDM system and the theoretical BER curve for the 16-QAM scheme. OFDM, which is used as a waveform in 4G technology, is implemented in Precoded MIMO systems. The mapping scheme for the precoded MIMO-OFDM system uses a 16-QAM mapping scheme. The comparison results are shown in Figure 5 above. Based on the simulation results shown in Figure 5, the precoded MIMO-GFDM system and the precoded MIMO-OFDM system produce the same BER performance. Meanwhile, both the precoded MIMO-GFDM system and the precoded MIMO-OFDM system have differences with the theoretical BER for the 16-QAM scheme of 0.0132 or -18 dB.

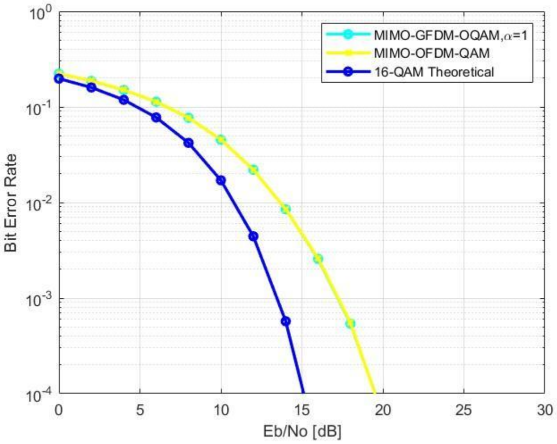

Fig. 5. Comparison of BER curves for the third scenario

4 Conclusion

In this research, the performance of the precoded MIMO-GFDM system based on BER parameters has been analyzed. The precoded MIMO-GFDM system produces a difference value with the theoretical BER curve for the 16-QAM scheme of 18 dB. In comparative testing between GFDM and OFDM, the MIMO-GFDM precoded system produces the same performance as the MIMO-OFDM precoded system. This means that the MIMO-OFDM precoded system with the theoretical BER curve for the 16-QAM scheme produces the same difference value as the MIMO-GFDM precoded system. The larger the value of the K and M variables for each GFDM block, the smaller the noise that affects the performance of the GFDM block.

References

[1] B. Ai, A. F. Molisch, M. Rupp, and Z. D. Zhong, "5G key technologies for smart railways," *Proc. IEEE*, vol. 108, no. 6, pp. 856–893, 2020, doi: 10.1109/JPROC.2020.2988595.

[2] M. Saideh, M. Berbineau, and I. Dayoub, "5G waveforms for Railway," *Proc. 2017 15th Int. Conf. ITS Telecommun. ITST 2017*, pp. 1–5, 2017, doi: 10.1109/ITST.2017.7972208.

[3] H. J. Taha and M. F. M. Salleh, "Multi-carrier transmission techniques for wireless communication systems: A survey," *WSEAS Trans. Commun.*, vol. 8, no. 5, pp. 457–472, 2009.

[4] J. Walrand and P. Varaiya, "High-Performance Communication Networks - Chapter 7: Wireless Networks," *High-Performance Commun. Networks*, pp. 305–361, 2000, doi: 10.1016/B978-0-08-050803-0.50012-5.

[5] R. He *et al.*, "High-Speed Railway Communications: From GSM-R to LTE-R," *IEEE Veh. Technol. Mag.*, vol. 11, no. 3, pp. 49–58, 2016, doi: 10.1109/MVT.2016.2564446.

[6] A. Gangwar and M. Bhardwaj, "An Overview: Peak to Average Power Ratio in OFDM

system & its Effect," *Int. J. Commun. Comput. Technol.*, vol. 01, no. 2, pp. 22–25, 2012, [Online]. Available: www.ijccts.org.

[7] M. C. P. Paredes and M. J. F.-G. García, "The Problem of Peak-to-Average Power Ratio in OFDM Systems," pp. 1–8, 2015, [Online]. Available: http://arxiv.org/abs/1503.08271.

[8] E. V Forschung *et al.*, "5G Waveform Candidate Selection," *5Gnow*, p. 100, 2014.

[9] D. Pinchon, P. Siohan, and C. Siclet, "Design techniques for orthogonal modulated filterbanks based on a compact representation," *IEEE Trans. Signal Process.*, vol. 52, no. 6, pp. 1682–1692, 2004, doi: 10.1109/TSP.2004.827193.

[10] J. H. Choi, B. J. Lim, Y. J. Kim, and Y. C. Ko, "Effect of timing and frequency synchronization errors on GFDM systems," *Int. Conf. ICT Converg. 2015 Innov. Towar. IoT, 5G, Smart Media Era, ICTC 2015*, no. 1, pp. 1322–1325, 2015, doi: 10.1109/ICTC.2015.7354807.

[11] T. Fusco, A. Petrella, and M. Tanda, "Sensitivity of multi-user filter-bank multicarrier systems to synchronization errors," *2008 3rd Int. Symp. Commun. Control. Signal Process. ISCCSP 2008*, no. March, pp. 393–398, 2008, doi: 10.1109/ISCCSP.2008.4537257.

[12] D. A. Feryando, "Performance analysis of regularized channel inversion precoding in multiuser MIMO-GFDM downlink systems," in *2017 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob)*, 2017, pp. 101–105, doi: 10.1109/APWiMob.2017.8283989.

[13] B. Farhang-Boroujeny and H. Moradi, "Derivation of GFDM based on OFDM principles," *IEEE Int. Conf. Commun.*, vol. 2015-Septe, pp. 2680–2685, 2015, doi: 10.1109/ICC.2015.7248730.

[14] I. F. Akyildiz, S. Nie, S. C. Lin, and M. Chandrasekaran, "5G roadmap: 10 key enabling technologies," *Comput. Networks*, vol. 106, pp. 17–48, 2016, doi: 10.1016/j.comnet.2016.06.010.

[15] Y. S. Cho, J. Kim, W. Y. Yang, and C. Kang, *MIMO-OFDM Wireless Communications with MATLAB*. 2008.

[16] Q. H. Spencer, C. B. Peel, A. L. Swindlehurst, and M. Haardt, "An introduction to the multi-user MIMO downlink," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 60–67, 2004, doi: 10.1109/MCOM.2004.1341262.

[17] B. M. Hochwald, C. B. Peel, and A. L. Swindlehurst, "A Vector-Perturbation Technique for Communication — Part II : Perturbation," pp. 1–24.

[18] N. Michailow *et al.*, "Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks," vol. 62, no. 9, pp. 3045–3061, 2014.

[19] K. Ni, M. Panji, K. Praja, and Y. D. Marimbun, "Analisis Perbandingan Modulasi 16-QAM Dan 64-QAM Pada Kanal Additive White Gaussian Noise Dan Rayleigh Fading Comparative Analysis of 16-QAM And 64-QAM Modulation In Additive White Gaussian Noise And Rayleigh Fading Channels," vol. 7, no. January, pp. 90–98, 2022.

[20] B. Sklar, *Digital Communications 2nd Edition: Fundamentals and Applications*. Upper Saddle River, New Jersey: Prentice Hall, 2001.