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PARAMETRIC ANALYSIS OF UFMC WITH 5G NR POLAR AND CONVOLUTIONAL CODES IN A MASSIVE MIMO SYSTEM

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ABSTRACT

The Fifth Generation (5G) wireless network's radio access strategies must meet dynamic and adaptable service requirements. The major demands in the current era of pervasive wireless networks are high throughput, reliability, and secure connectivity. 5G New Radio (NR) air interface is a major transition to new modulation and channel coding techniques to reduce redundancy, latency, and complexity. Convolutional codes were used in 4G and polar codes in 5G to code channels for control information in the uplink and downlink. This research aims to investigate the 4G channel codes and provide analytical results for comparing them to the 5G polar codes in Ultra-Reliable Low-Latency Communication (URLLC) applications with short block-length transmissions. The research implements Universal Filtered Multi-Carrier (UFMC) modulation, a suitable technique for short burst transmissions. Channel coding is applied to enhance reliability, considering Polar codes as major 5G candidates for short packet transmission. The comprehensive system is simulated in a massive Multiple Input Multiple Output (MIMO) scenario. The impact of antenna array size in MIMO and UFMC parameters and sub-band size are investigated. The major contribution of the work is that the Bit Error Rate (BER) performance of Polar codes is enhanced with an SNR gain of ~7dB with a 64x16 MIMO UFMC system compared to convolutional codes. Moreover, the concatenated polar and convolutional codes are used, which results in an additional SNR boost of about 3dB. This research reveals that mission-critical applications in 5G can benefit from the flexibility and improved error rate performance offered by the combination of UFMC, Polar codes, and massive MIMO.

I. INTRODUCTION

Enhanced mobile broadband (eMBB), which offers exceptionally high data bandwidth with applications like ultra-high definition (UHD) videos; massive machine type communication (mMTC), for Internet of Everything (IoE) applications having massive low-cost, low-powered devices; and URLLC used in autonomous vehicles, remote surgery, etc., are the primary use cases for 5G networks. These use cases must support high-speed data transmissions of small packets with high reliability [1]. URLLC facilitates delay-sensitive applications such as remote surgery, Augmented reality, industry 5.0, intelligent transport system, etc. The short packet size is to be considered to reduce latency. However, reducing the packet size may cause a loss in coding gain [2]. The permissible latency in URLLC services set by the International Telecommunication Union (ITU) is for a standard packet size of 32 bytes, which is 1 millisecond, with a reliability of $1x10^{-5}$ [3-4]. To fulfill these requirements, the critical enablers considered in the research are channel coding algorithms, multicarrier modulation waveform, and massive MIMO antenna technology.

The transition from a cell-centric to a user-centric design approach for network densification with limited spectrum needs new radio access techniques [5]. The multicarrier waveform is to be chosen as an air interface, which is flexible and reliable in heterogonous networks [6]. A transmission technique with extremely low latency is made possible by highly brief frames. The waveform is to be compatible with short burst transmissions so that it can enable short Transmission Time Intervals (TTIs) with fast uplink/downlink switching [7]. Major waveform contenders for

5G, like Generalized Frequency Division Multiplexing (GFDM), Filter Bank Multicarrier (FBMC), Filtered-Orthogonal Frequency Division Multiplexing (F-OFDM), and Universal Filtered Multi-Carrier (UFMC), are reviewed and analyzed in [9-15]. UFMC is the best choice for a system targeting short-burst transmissions into the overall system design [7].

In UFMC, the available bandwidth is divided into sub-bands and filtered independently. Along with the modulation technique, Massive MIMO technology is integrated, and hundreds of antennas are implemented at the next generation Node B (gNB) to improve network capacity and throughput [16]. The system processing gain tends to be infinite as the number of antennas (W) at the gNB increases [17]. 5G NR is the imminent evolution of next-generation mobile technology to enhance spectral efficiency, signal efficiency, data rate, and connection density [18].

To suit the varied requirements of URLLC, the channel coding must be redesigned and implemented to achieve ultra-high reliability. In URLLC, short blocks are required to reduce the latency. On the contrary, the short blocks reduce coding gain and degrade dependability. However, boosting reliability necessitates adding more redundancy bits, increasing the delay.

As a result, it is crucial to choose the channel coding technique carefully in this case. 5G polar codes are designed mainly for short block transmission to resolve the latency issue needed in the URLLC use case [19]. In 5G NR, polar codes are applied for encoding control information and are considered a major contender of 5G channel coding techniques [20]. In this paper, the hybrid system is designed using a UFMC waveform and a massive MIMO channel with polar coding. An analytical framework is discussed to understand the numerology required for UFMC, antenna array size in massive MIMO, and polar coding.

II. UNIVERSAL FILTERED MULTICARRIER (UFMC)

UFMC modulation technique is based on filtering the sub-bands. Suppose the total M sub-carriers are available and grouped into several sub-bands of size Q, fulfilling M=PQ [21]. Q Subcarriers are modulated by the Quadrature Amplitude Modulation (QAM), and the modulated symbols in each sub-band are converted into frequency symbols for orthogonal time domain subcarriers by the N-point IFFT module.

Each sub-band is filtered with a Dolph-Chebyshev prototype filter of length l. Filtering reduces out-of-band emission (OOBE) and inter-carrier interference (ICI) [22]. In the proposed system, the Dolph- Chebyshev filter is used. Its time domain and frequency domain characteristics for a filter length of 43 are shown in Figure 1. In Dolph Chebyshev, the filter width of the main lobe is minimized for a given α side lobe attenuation, and the mathematical expression of the Chebyshev window is shown in equation (1) [23].

$$f= \frac{\cos\{N.cos^{-1}[\beta \cos\left(\frac{\pi k}{N}\right)]\}}{\cos[N\, cosh^{-1}(\beta)]} \quad (1)$$

Where N is the size of IFFT, k=0, 1…, M-1, $\beta = \cosh\{\frac{1}{N} cosh^{-1}(10^{\alpha})\}$, α = Side lobe attenuation (2,3,4).

Eventually, the resultant UFMC signal is mathematically written as equation (2):

$$X_{UFMC} = \sum_{k=1}^{C}\sum_{i=1}^{B} F_{i,k}V_{i,k}s_{i,k} \quad (2)$$

Where $F_{i,k}$ is a filter impulse response matrix; $V_{i,k}$ is the IFFT matrix; $s_{i,k}$ is a time domain symbol. The complete UFMC modulation is shown in Figure. 2.

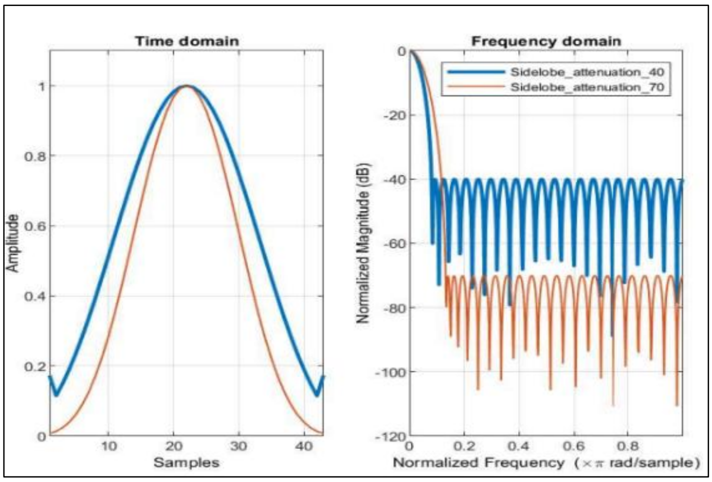

Figure 1: Time and frequency characteristics of the Chebyshev filter.
Source: Authors, (2025).

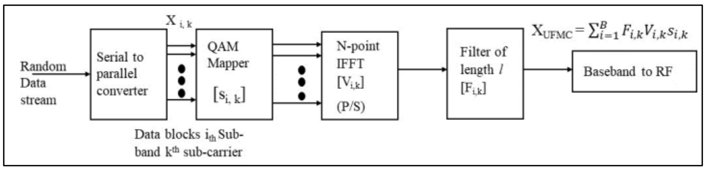

Figure 2: UFMC Modulation.
Source: Authors, (2025).

The UFMC waveform achieves better spectrum utilization with no cyclic prefix (CP), and sub-band filtering reduces side lobes. UFMC waveform is adaptable as per the requirement and facilitates adjusting the sub-band size and filter length [24]. With its flexible and simple design, the UFMC is suitable for short packet communication making it a suitable waveform candidate for URLLC applications [25].

III. CHANNEL CODING

Channel coding is being employed to overcome the impact of a channel for reliable data transmission. This strategy entails adding redundant bits to the message being transmitted so that the transmission errors can be recognized by the receiver, and then possibly corrected. In 4G network linear error-correction codes like Turbo and Convolutional codes are used. The Third Generation Partnership Project (3GPP) proposed Low Density Parity Check (LDPC) codes and Polar codes for 5G network.

III.1 CONVOLUTIONAL CODE

Random data bits are generated in every sub-band and encoded using convolutional coding. In convolutional coding, n output encoded bits are generated with k successive information bits, giving the code rate R = k/n. The encoder is designed with a shift register of length K, called the constraint length [26]. The convolutional encoder (1, 2, 3) with code rate ½, is shown in Fig. 3. The output parity check equations are given by (3) and (4), where the D represents the memory element:

$$C_k^{(1)} = D_0 \oplus D_1 \quad (3)$$

$$C_k^{(2)} = D_0 \oplus D_1 \oplus D_2 \quad (4)$$

The generator polynomials g(x) are shown in equations (5) and (6):

$$g^{(1)}(x) = 1 + x \quad (5)$$

$$g^{(2)}(x) = 1 + x + x^2 \quad (6)$$

Final encoding is done by equation (7):

$$C_i^{(j)}=\sum_{u=0}^{2} D_i - ug_u^{(j)} \quad (7)$$

To reduce the impact of a burst error, the encoded bit sequences are spread out using an interleaver [27].

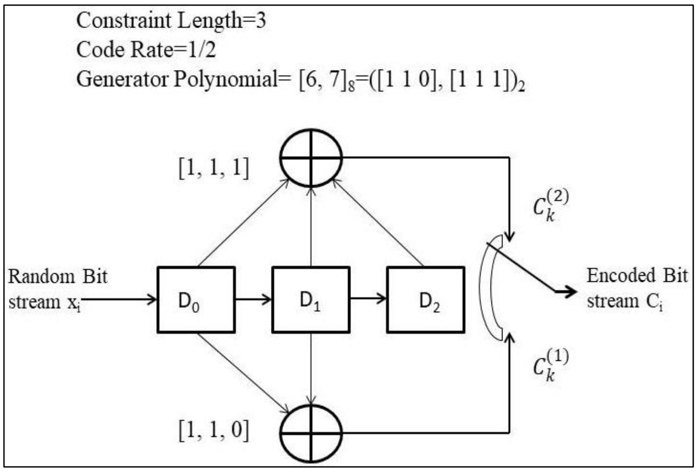

Figure 3: Convolutional Encoder.
Source: Authors, (2025).

II.2 POLAR CODE

The Polar codes are low-complex channel codes adopted for control channels in 5G NR systems. The channel polarization phenomenon transforms memoryless, binary-input, output-symmetric (MBIOS) channels by generating N' synthetic bit channels. The new synthesized channels are polarized. Polarization refers to the transmission of individual bits with varying reliability. Reliability refers to the different probability of being decoded correctly. The prediction of the reliability of each synthetic channel allows them to be arranged according to the reliability order [28]. The recursive structure of the polarizing matrix G_N, as shown in equations (2) and (3), allows for the reduction of encoding complexity [29].

$$G_{N'} = G_2^{\otimes n} \quad (8)$$

$$G_{N'} = G_{N'/2}{}^{\otimes 2} = \begin{pmatrix} G_{N'/2} & 0 \\ G_{N'/2} & G_{N'/2} \end{pmatrix} \quad (9)$$

The polar code of length N' has the constraint that it should be of powers of two, but K can be of any size in the information set. So, to achieve the desired code rate R=K/E, the rate matching concept must be applied in polar codes. In 5G, this rate-matching problem is achieved using techniques like puncturing, shortening, and extending [30]. The polar coding algorithm is shown in Figure 4.

A variety of algorithms are available for decoding. Arikan proposed the Successive Cancellation (SC) technique in 2009 [30] as a decoding algorithm for Polar Codes. SC method is not suitable for a smaller number of block lengths as it takes only one path from the decoding paths. Decoding stores a set of prospective paths for this Successive Cancellation List (SCL). The SCL decoder keeps track of L paths simultaneously. With the increase in the list size, its performance increases at the cost of implementation complexity [31]. Let $\hat{u}_i$ be estimate of the Source block after receiving $y_1^{N'}$, the bits $\hat{u}_i$ are estimated successively.

L distinct decoding paths= $\hat{u}_i^{(i-1)}(1), \ldots . \hat{u}_i^{(i-1)}(L)$ after the (i−1)[th] bit has been decoded. For every path t ∈ {1, . . . , L}, there are two choices for $\hat{u}_i(t)$. Out of the resulting 2L paths, the L paths with the highest metric are preserved. When bit N' is reached, the route with the highest metric is set as the decoded codeword [32].

IV. MASSIVE MIMO CHANNEL

In 5G massive MIMO systems, gNB is equipped with W receiving antennas with digital transceiver chains capable of spatially multiplexing T transmitting antennas. Massive MIMO system's uplink is implemented where there are more receiving antennas than transmitting antennas: W/T > 1 [33]. Data is transmitted after UFMC modulation of the massive MIMO channel H for Rayleigh fading [34].

The detection of the desired signal at receiving end is done by nullifying all the interference signals. It is processed by multiplying it with a suitable weight matrix. In our proposed system Zero forcing detection is applied. In Zero forcing signal detection the interferences are negated by weight matrix WZF represented in equation (10), called as Moore-Penrose pseudo-inverse of H.

$$W_{ZF}=(H^H H)^{-1} H^H \quad (10)$$

It inverts the effect of the channel and gives the expected value $\hat{x}_{ZF}$ by equation (6):

$$\hat{x}_{ZF}=S\ \{(H^H H)^{-1} H^H\} Y \quad (11)$$

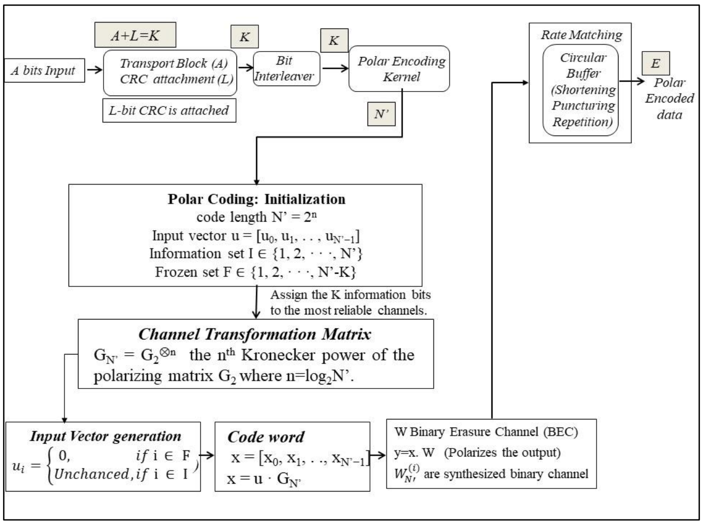

Figure 4: Polar Coding Algorithm.

Source: Authors, (2025).

V. SIMULATION FRAMEWORK AND RESULTS

The system is designed with 4G based Convolutional codes and 5G NR specifications based polar codes with UFMC in massive MIMO scenario. The simulation is done using MATLAB software version 2022b. The control parameters are considered in three sections of simulation as shown in Figure 5. The simulation parameters are shown in Table I. In this paper, the key performance indicator is bit error rate (BER) with respect to signal to noise ratio (SNR) (Eb/N0) is considered for short block transmission and low code rate particularly for URLLC use case scenario.

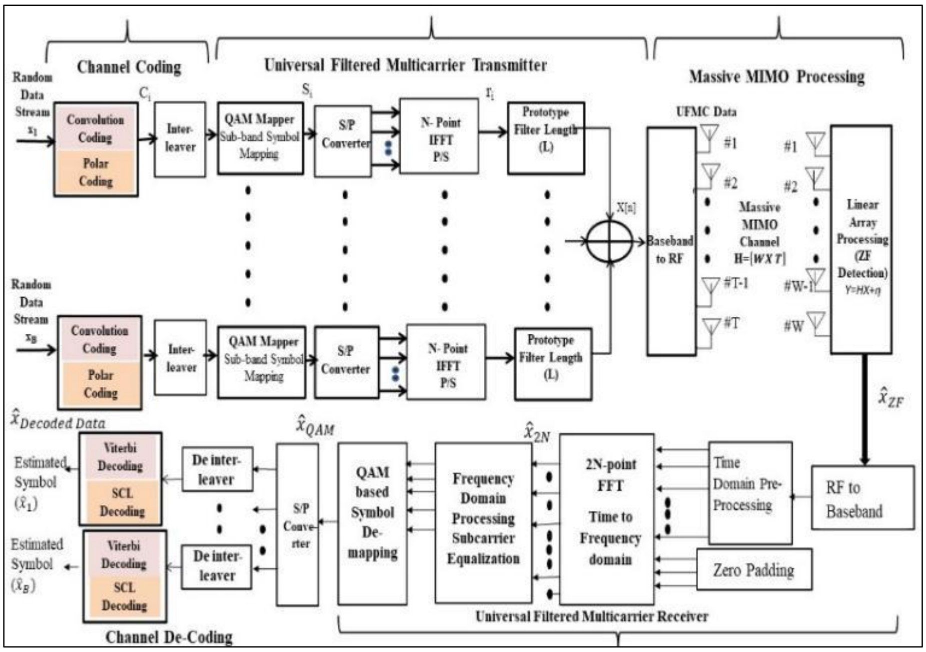

Figure 5: System framework for parametric analysis.
Source: Authors, (2025).

Table 1: Simulation Parameters.

Parameter	Value
UFMC Parameters	
Number of Sub-bands	10
Sub-band size	20
Sub-band Offset	156
Modulation order	64 QAM
Size of FFT	512
Filter	Dolph-Chebyshev
Filter Length (*l*)	43
Side lobe attenuation (α)	40dB
Massive MIMO channel Parameters	
Number of Transmitting	16
Number of Receiving Antenna at gNB (W)	20-100
Linear Array processing	Zero Forcing
Convolutional Coding Parameters	
Code rate (R)	1/2
Constraint Length	3
Channel Decoding	Viterbi
Polar Coding Parameters	
Decoding List length (L)	8
Polar Decoding Algorithms	List Successive Cancellation (SCL)
Code rate R	1/2
Message length K	132
The rate matched output	256

Source: Authors, (2025).

Firstly, the system is simulated for UFMC waveform with Convolutional and polar codes in MIMO antenna implementation. Figure 6 shows that the performance of the coded signal significantly outperforms the standalone UFMC waveform in a 64x16 MIMO system. The BER curve shows that a gain of ~7 dB is achieved in polar codes compared to Convolutional codes.

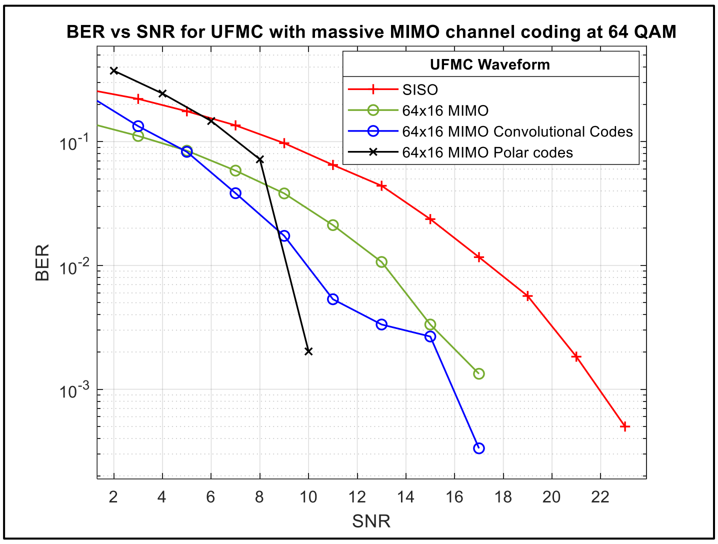

Figure 6: BER versus SNR performance of UFMC waveform with different channel codes.
Source: Authors, (2025).

The system designed in [35], is based on MIMO but implemented a 4G-based Orthogonal Frequency Division Multiplexing (OFDM) waveform. The 5G NR-based UFMC waveform is implemented to enhance the BER performance. The comprehensive system of UFMC waveform in a massive MIMO channel model is designed and simulated.

The simulation is done at 64 QAM, varying the antenna array size at gNB (W) from 20 to 100. The significant outcome of the UFMC-based massive MIMO system simulation with Convolutional codes, so increasing the number of antennas (W) at gNB improves the system performance by providing good throughput yet at low SNR, shown in Figure. 7.

From Figure. 8, BER output for Polar coded UFMC in massive MIMO is that it requires SNR 8dB to achieve zero BER with 100 antennas at gNB. However, to achieve the same BER with 20 antennas at gNB, the required SNR is>25 dB. So, by increasing the antenna array size, there is enormous potential for BER improvement and enhancing data reliability.

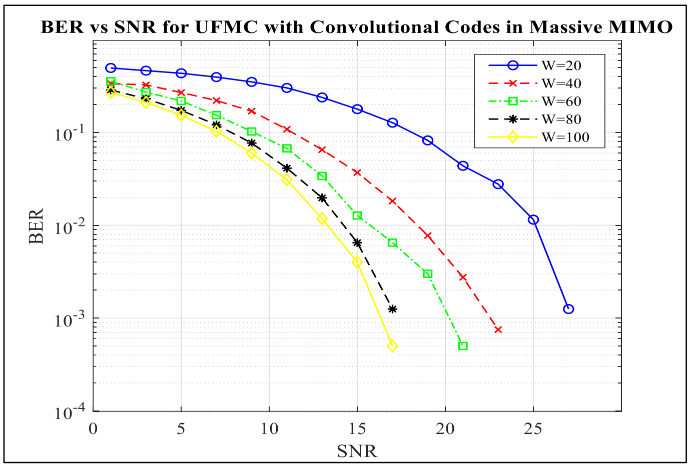

Figure 7: BER Performances for UFMC with Convolutional Codes with Variable gNB antenna array size
Source: Authors, (2025).

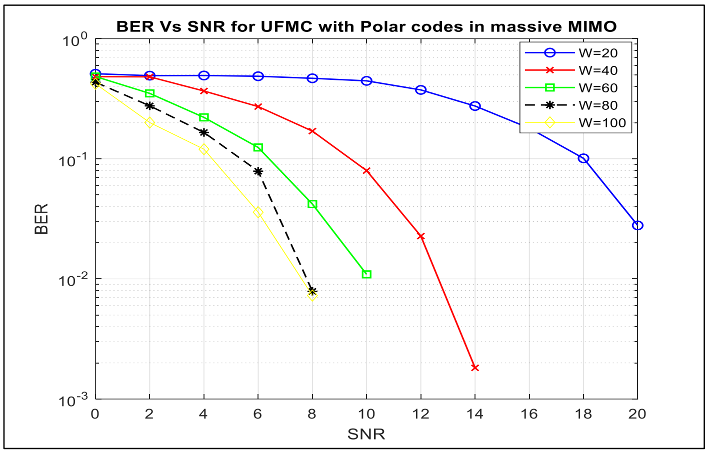

Figure 8: BER performance of Polar coded UFMC system with Variable gNB antenna array size.
Source: Authors, (2025).

Further in the system, CRC-aided Polar codes are used with different CRC lengths to improve the BER performance. Figure 9 shows the impact of CRC length on the system's BER. The larger the CRC length, the better the BER performance, but the computational complexity increases.

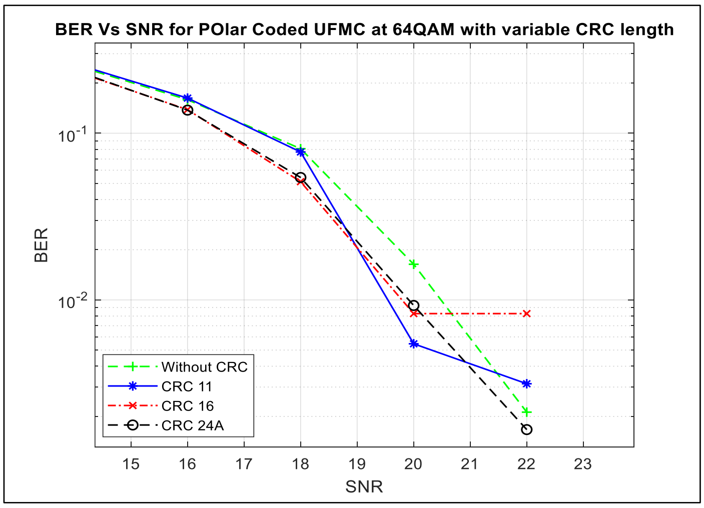

Figure 9: BER performance of Polar coded UFMC system for variable CRC length
Source: Authors, (2025).

For the parametric analysis, the UFMC waveform is analyzed with varying sub-band size (K). The Power Spectral Density (PSD) for UFMC is shown in Figure 10 with variable sub-band size. It is seen from PSD that as the sub-band size increases the spectral efficiency enhances as more subcarriers support higher throughput and efficient utilization of bandwidth.

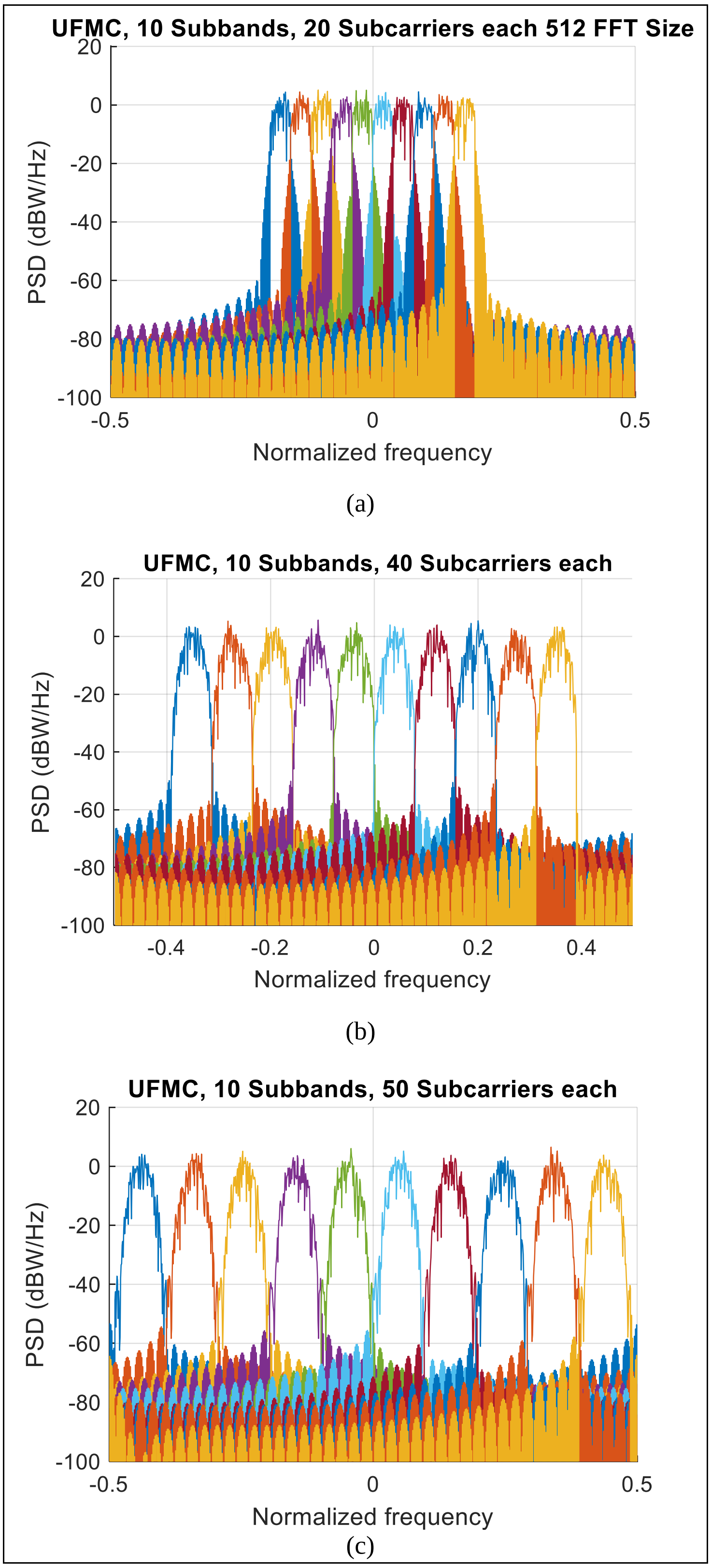

Figure 10: PSD for UFMC Waveform with (a) sub-band size=20 (b) sub-band size=40 (c) sub-band size=50.
Source: Authors, (2025).

Further, the system is simulated with 20 antennas at gNB and a variable UFMC subband size. From the output curve shown in Figure 11, it is observed that different subband sizes affect the UFMC BER performance. So, the size of the subband is to be selected to optimize the performance. The smaller the subband size, the better the BER performance.

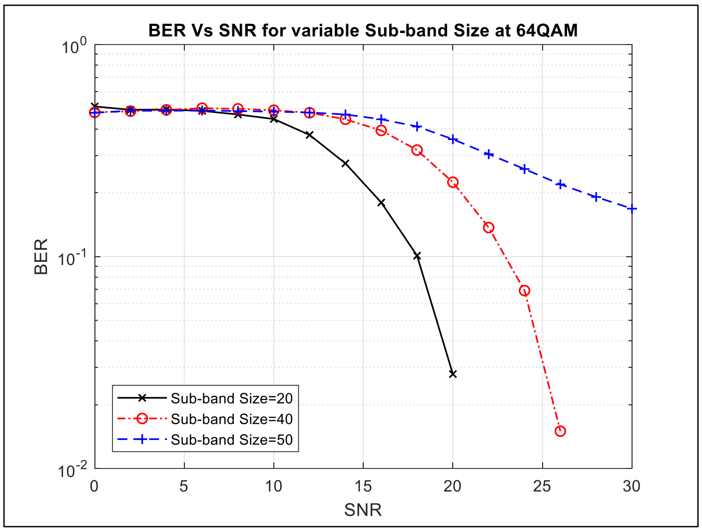

Figure 11: BER vs SNR for Polar coded UFMC Waveform with variable sub-band size.
Source: Authors, (2025).

Concerning [36], concatenation schemes of polar codes with convolutional codes result in frame error rate reduction with the frame length. This joint technique shows a significant improvement over standalone polar code. In the simulated system, convolutional codes are applied as inner and polar codes as outer codes. The 64x16 MIMO antenna array is implemented with 64QAM order. Figure 12 concludes that combining convolutional and polar coding provides an SNR gain of ~3 dB.

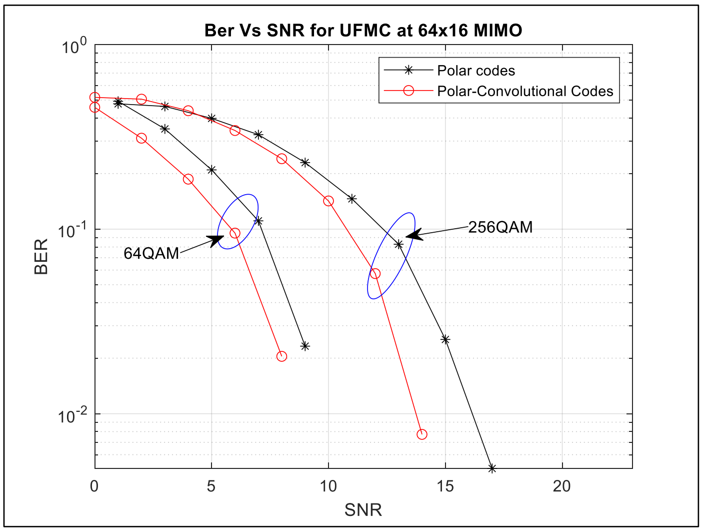

Figure 12: BER performance of joint convolutional and polar coded UFMC system with variable QAM order
Source: Authors, (2025).

VI. CONCLUSIONS

This paper analyzes the parametric performance of a massive MIMO-based system with Convolutional and Polar codes in UFMC waveform for URLLC use case with short block transmission. The system with different MIMO antenna array size and their impact on the BER is being considered for 5G systems. The Convolutional codes provide the SNR gain of 4dB as compared to the uncoded UFMC signal. Channel coding and its integration with UFMC provide flexibility in selecting the filter characteristics and sub-band size.

UFMC and Polar codes provide flexibility with better error rate performance to be compatible with mission-critical applications in 5G. Simulation results conclude that keeping CRC length to 24, the smaller sub-band size, the higher sidelobe attenuation, and the larger antenna array size will fulfill Ultra reliability. The short block provides ultra-low latency, and polar coding and UFMC are the most promising techniques compatible with short-burst communications. Additionally, the concatenation of convolutional and polar codes enhances BER performance.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Smita Prajapati, Divya Jain, and Neha Kapil.
Methodology: Smita Prajapati, Divya Jain.
Investigation: Smita Prajapati
Discussion of results: Smita Prajapati, Neha Kapil.
Writing – Original Draft: Smita Prajapati
Writing – Review and Editing: Smita Prajapati and Divya Jain.
Approval of the final text: Smita Prajapati, Divya Jain, and Neha Kapil

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