Implementation of Turbo Coded Filtered OFDM in 5G Networks

Kaustubh Ranjan Singh[1*], Harshit[1], Japnoor Singh[1], Jatin[1]

[1*]ECE Department, Delhi Technological University, New Delhi, India.

*Corresponding author(s). E-mail(s): ***kaustubh@dtu.ac.in***;
Contributing authors: ***harshit_ec20b12_61@dtu.ac.in***;
japnoorsingh_ec20b1_01@dtu.ac.in;
jatin_ec20a13_64@dtu.ac.in;

Abstract

This paper investigates Turbo-Coded Filtered-Orthogonal Frequency Division Multiplexing (TC-F-OFDM) as a potential candidate for waveforms for 5G networks. Here, we analyze the performance of Turbo-coded OFDM-based wireless networks and demonstrate improvements using Filtered OFDM techniques. The study incorporates different code rates under noisy and faded channel conditions, Doppler shifts on Turbo Decoding (BCJR), and Peak-to-Average Power Ratio (PAPR) analysis for coded and uncoded F-OFDM conditions. The results obtained show that TC-F-OFDM offers significant performance improvements for spectral efficiency (SE) on account of reduced Out-of-Band Emissions (OOBE) and improved Bit Error Rate (BER) performance under fading channels. While PAPR in the case of F-OFDM is worse than conventional OFDM, turbo-coding offers a marginal improvement compared to uncoded F-OFDM.

Keywords: 5G networks, Turbo codes, Filtered-OFDM (F-OFDM), Orthogonal Frequency Division Multiplexing (OFDM), Spectral efficiency, Out-of-Band Emissions (OOBE), Bit Error Rate (BER), Peak-to-Average Power Ratio (PAPR), AWGN channel, Fading channel, Doppler shift.

1 Introduction

Cellular networks have evolved in order to meet increasing demands of cellular capacity. New Radio (NR) has been designated as the air interface standard for 5G wireless communications by the Third Generation Partnership Project (3GPP), which comes after the rollout of Universal Mobile Telecommunications System (UMTS) technologies for 3G and Long Term Evolution (LTE) for 4G. 5G operates across both sub-6 GHz and mmWave frequencies. Beyond 5G networks, 6G will explore even higher frequencies, potentially including terahertz bands, to achieve unprecedented data rates and capabilities [1].

Orthogonal Frequency Division Multiplexing (OFDM) has been fundamental to the evolution of cellular telephony from primitive Wideband Code Division Multiple Access (WCDMA)-based 3G technologies to more advanced 4G and 5G technologies. It is a technique for encoding binary data onto multiple carriers instead of the previous single-carrier modulation techniques. OFDM allows for more efficient utilization of the available spectrum and it also minimizes multipath fading effects [2]. The frequency-selective nature of wireless channels is modeled based on multipath component analysis under different fading conditions.

In addition to fading, other problems with the wireless channel include shadowing and Doppler shift, which cause the signal frequency to change as a result of the relative motion of the transmitter and receiver and makes communication more prone to errors. To address this, OFDM is clubbed with forward error correction schemes to detect and correct errors. However, error-corrected codes occupy more bandwidth and a smaller data rate than uncoded data. Given the limited resources at play, it is crucial to efficiently utilize the bandwidth without sacrificing the data rates.

Claude Shannon, in his pioneering work [3], established the Shannon limit, which dictates the maximum data rate at which reliable communication can occur over a noisy channel. Since then, the design of coding techniques has evolved from conventional linear block codes to turbo and LDPC codes, whose BER performance approaches the Shannon Limit [4]. The design of decoders plays a significant role in achieving improved performance. The soft output decoding performance of Bahl-Cocke-Jelinek-Raviv (BCJR), which utilizes the Bit-wise Maximum a Posteriori (MAP) method has shown performance increments than Soft Output Viterbi Algorithm (SOVA) for turbo codes [5].

Conventional OFDM remains the primary modulation scheme for 5G, but it exhibits high Out-of-Band- Emissions (OOBE) and Peak-to-Average Power Ratio (PAPR), making it difficult to meet 5G requirements. Research efforts are being made in order to overcome these bottlenecks through Filtered-OFDM (F-OFDM) in 5G networks [6]. F-OFDM applies spectral filtering to traditional OFDM symbols, reducing out-of-band emissions and improving spectral containment, thus enhancing spectral efficiency and mitigating interference in crowded frequency bands.

The use of error-correcting codes in OFDM-based Quadrature Amplitude Modulation (QAM) networks has shown improved performance metrics like BER. The role of F-OFDM to improve performance and efficiency in 5G networks is being studied. The following are the contributions made by this paper:

- Performance analysis of OFDM was done with turbo codes.
- For improving the proposed system, F-OFDM technique was implemented which gave better results.
- Comparative study was performed for different code rates over AWGN channel and fading conditions.

- Impact of Doppler shift on turbo decoding is studied.
- PAPR analysis for coded and uncoded F-OFDM was studied.

This paper is organized as follows: Section II discusses OFDM implementation, Section III discusses F-OFDM implementation; whereas Section IV discusses Turbo Code Implementation, followed by Results in Section V and conclusions thereafter.

2 OFDM

An OFDM system utilizes the properties of orthogonal gated sinusoids to avoid distortion caused by multipath channels without using complex equalizers. An OFDM symbol consists of a superposition of subcarriers, each carrying data in the frequency domain (modulating the carrier's amplitude and phase). The symbols contain an integer number of cycles in that interval to maintain the necessary orthogonality condition, allowing for efficient usage of channel resources. They can be, therefore, closely packed without causing interference. The subcarriers occupy a sub-channel, formed by partitioning the wideband channel such that each sub-channel constitutes a narrow-band flat fading channel instead of frequency-selective bands. Such an arrangement allows combating against deep fades in the multipath channel. Fig. 1. shows the frequency representation of an OFDM signal.

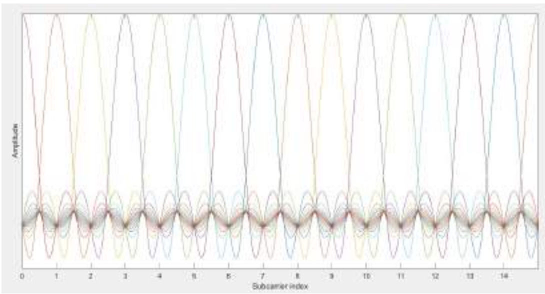

Fig. 1 Subcarriers in an OFDM symbol

The time domain superposition of these subcarriers, x_n, is the equivalent of the inverse Discrete Fourier Transform (IDFT) of complex numbers, X_k, obtained from digital modulation, shown as:

$$x_n = \sum_{k=0}^{N-1} X_k e^{j2\pi \frac{k}{N} n}; 0 < n < N \tag{1}$$

This process is implemented using the Inverse Fast Fourier Transform (IFFT) on the transmitter end and recovered using the Fast Fourier Transform (FFT) on the receiver end. The addition of a cyclic prefix in OFDM allows mitigation of Inter Symbol Interference (ISI), given that the duration of the CP is more than the delay spread of the multipath channel. Fig. 2. shows a block diagram of an OFDM system.

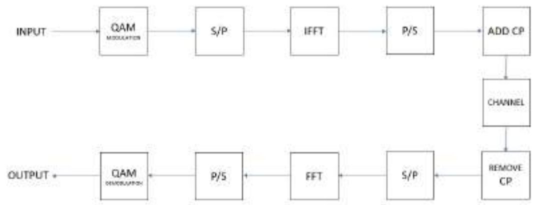

Fig. 2 OFDM Block Diagram

3 F-OFDM

OOBE are unwanted frequency emissions outside the OFDM symbol's occupied bandwidth into adjoining symbol channels. High OOBE in OFDM is a result of its sinusoidal nature which causes issues in the utilization of the channel bandwidth efficiently and also increases Adjacent Channel Interference (ACI) and ISI [7]. If it is not suppressed, bit errors in adjacent transmissions are very likely to happen. Filtering has emerged as a competent way of increasing spectral containment, giving rise to proposed 5G technologies like F-OFDM. The filtering in these technologies can be on a sub-carrier or sub-band basis. An F-OFDM system uses sub-band filtering to reduce OOBE [8]. The signal is recovered using a matched filter followed by the generic OFDM receiver on the receiver side. Figure 3 shows the structure of the F-OFDM transceiver.

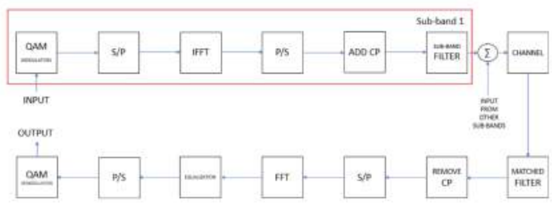

Fig. 3 F-OFDM Block Diagram

Filter design is crucial to reduce OOBE sufficiently. Windowed-Sinc filters have a rectangle frequency response and flat pass-band over subcarriers, making them a popular choice for sub-band filters. The Sinc filter is generally truncated using the Hanning window [9]. If L is the length of the window and $L = N+1$ then Hanning window coefficients are generated using equation (2).

$$w(n) = 0.5(1 - cos(2\pi\frac{n}{N})), 0 \leq n \leq N \tag{2}$$

Equation (3) represents an F-OFDM symbol, where *f(i)* is the filter response and N_{CP} is the length of the cyclic prefix.

$$x_{fofdm}(i) = \frac{1}{N} \sum_{l=-\infty}^{l=\infty} f(i-l) \sum_{k=0}^{N-1} x_k(m) e \frac{j2\pi k(i - N_{CP})}{N} \tag{3}$$

The filter length in F-OFDM is shorter compared to other proposed technologies like Filtered Multi-Bank Carrier (FBMC) [10], which makes it advantageous in terms of latency and data rate. In this case, filter length is set to $\frac{x_{fofdm}}{2} + 1$

4 Turbo Codes

Turbo codes make use of parallel concatenated convolutional codes, which are essentially concurrent recursive systematic convolutional encoders. Each encoder processes information bits, *u(k)*, and generates encoded bits, *v(k)*, using its generator polynomial *G(D)* (D represents the delay operator). The encoding process can be mathematically represented as in equation 4.

$$v(k) = u(k) * G(D) \tag{4}$$

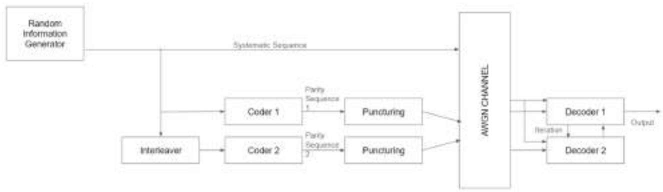

Fig. 4 Turbo Code Block Diagram

Fig. 4 displays the Turbo encoder and decoder block diagram. The randomly generated input and the encoder's two input bits are mixed by an interleaver, whose parity bits can be punctured. The transmitted signal is affected by AWGN noise. at the receiver, using the selected decoding algorithm (BCJR) the decoders decode the signal and estimate it after a pre-determined number of repetitions.

The proposed system employs turbo codes constructed from two convolutional encoders defined by the trellis structure for convolutional encoder design principles based on [11, 14]. The specific generator polynomials are chosen to achieve a balance between decoding complexity and error correction performance. The code rates for the performance study are 1/2 and 1/3. [12][15].

To improve the iterative decoding process and mitigate burst errors, random interleaving is implemented before transmission and de-interleaving at the receiver [13].

The BCJR (Baum-Welch soft-decision iterative decoding) algorithm iteratively refines estimates of transmitted bits by exchanging information between the two component decoders. BCJR employs soft-decision decoding achieved through LLRs (Log-Likelihood Ratios), incorporating the uncertainty in received signals for better error correction compared to hard-decision decoding, as detailed in [14]. The selection of the BCJR algorithm stems from its demonstrably superior performance compared to other decoding algorithms, particularly in channels with moderate to high noise levels, as encountered in the proposed system. BCJR's iterative decoding with soft-decision information (LLRs) leads to a significant reduction in Bit Error Rate (BER) compared to simpler algorithms like Viterbi decoding [16] which makes BCJR a compelling choice for decoding applications of Turbo codes.

5 Results

The simulations were conducted over AWGN and fading conditions, comparing the Power Spectral Density (PSD) and BER performance of OFDM and F-OFDM with Turbo codes. Table 1 summarizes the system model parameters:

System parameter	**Parameter setting**
Symbol Mapping	QAM-64
FFT/IFFT size	1024
Length of cyclic prefix	72
Filter length	513
Windowing	Hanning
Code rates	1/2, 1/3
Fading	Rayleigh
Noise	AWGN

5.1 PSD COMPARISON BETWEEN OFDM and F-OFDM

Fig. 5, Fig. 6 and Fig. 7 show the comparison of PSD of OFDM and F-OFDM for different code rates. It is clearly seen that the OOBE are suppressed in the case of F-OFDM for all code rates as compared to OFDM. However, it is observed that OOBE slightly increases with code rate.

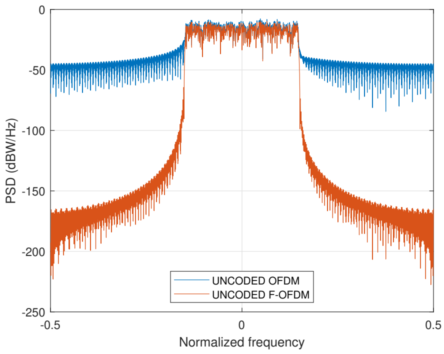

Fig. 5 PSD of uncoded OFDM and F-OFDM

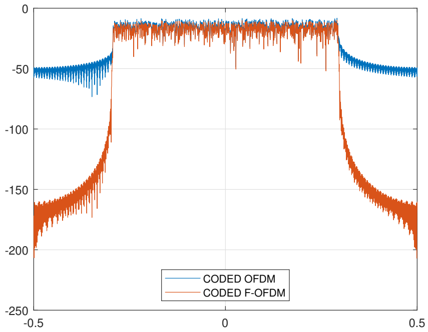

Fig. 6 PSD of coded OFDM and coded F-OFDM (1/2 CODE RATE)

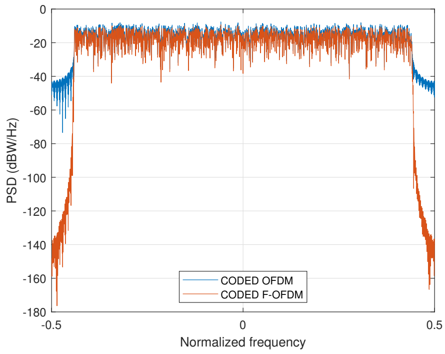

Fig. 7 PSD of coded OFDM and coded F-OFDM (1/3 CODE RATE)

5.2 BER ANALYSIS OVER AWGN CHANNEL

Fig. 8 and Fig. 9 show the BER analysis of OFDM and F-OFDM over the AWGN channel using different code rates. Turbo codes have improved the BER performance significantly for both OFDM and F-OFDM. F-OFDM outperforms OFDM in terms of BER performance. For 1/3 code rate OFDM has a coding gain of approximately 10 dB for 10^{-3} BER, which is similar to the coding gain achieved at 1/2 code rate.

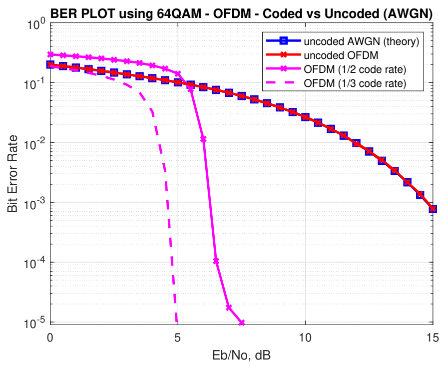

Fig. 8 BER plot of OFDM over AWGN channel

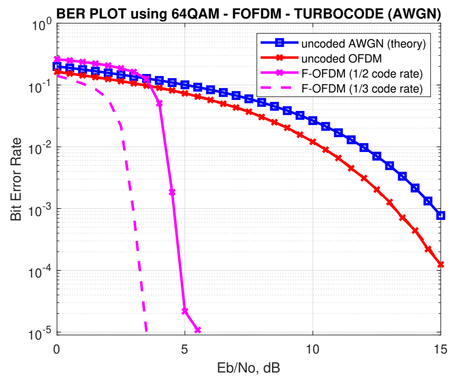

Fig. 9 BER plot of F-OFDM over AWGN channel

5.3 BER ANALYSIS OVER RAYLEIGH CHANNEL

The BER performance of OFDM and F-OFDM systems follows the same trend under fading conditions as well. Fig. 10 and Fig. 11 show BER vs SNR plot for rayleigh fading conditions, in which F-OFDM is able to outperform OFDM, implying that filtering also helps in countering multipath channel effects.

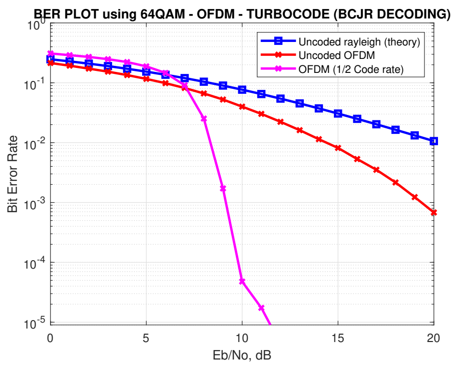

Fig. 10 BER vs EB/No of OFDM over Rayleigh channel

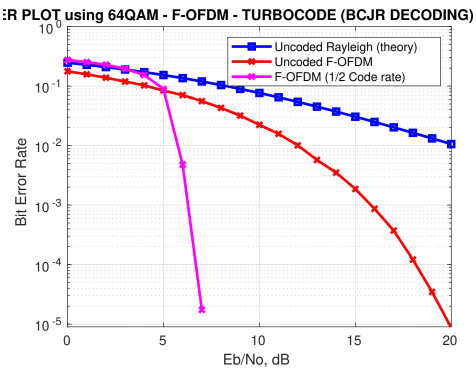

Fig. 11 BER vs EB/No of F-OFDM over Rayleigh channel

5.4 PAPR COMPARISON

The Complementary Cumulative Distribution Function (CCDF) against PAPR plot of F-OFDM and uncoded OFDM, as well as turbo coded OFDM and F-OFDM with a 1/2 code rate, are displayed in Fig. 14. Despite improving spectral containment and BER performance, filtering is unable to decrease PAPR performance of OFDM. The PAPR performance of F-OFDM is marginally degraded than generic OFDM. However, the implementation of turbo code improves the PAPR performance marginally.

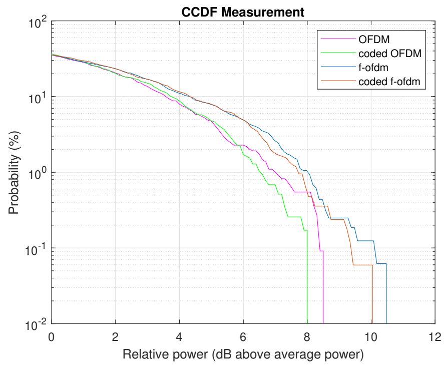

Fig. 12 PAPR comparison of uncoded and coded OFDM and F- OFDM

6 Conclusion

In this paper, we designed Turbo-coded F-OFDM to study its candidature as a proposed 5G waveform. It is observed that by reducing OOBE, a better spectral efficiency is obtained. BER analysis shows significant performance improvement as well even in multipath fading conditions, through the proposed design. Also, PAPR is not reduced compared to generic OFDM. However, the implementation of Turbo coding improves PAPR marginally compared to uncoded F-OFDM. Hence, Turbo-coded F-OFDM solidifies itself as a major candidate waveform to improve 5G networks.

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