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Investigations on Filtered OFDM with Selective Mapping Method and Partial Transmit Sequence Technique for Future Generation Mobile Communication Systems

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Abstract:

Future generation mobile communication system requires asynchronous transmission of data, reduced out-of-band power emission, low peak-to-average power ratio, low latency, high data transmission rate, better spectrum, energy, and power efficiency, etc. Investigations on suitable waveform candidates for future-generation mobile communication have been reported in this paper. Filtered Orthogonal Frequency Division Multiplexing (F- OFDM), F- OFDM with Selective Mapping Method (SLM), and F- OFDM with Partial Transmit Sequence (PTS) technique, have been investigated. Its performances have been evaluated in terms of peak-to-average power ratio (PAPR), bit error rate (BER), and out-of-band power emissions. F–OFDM is a suitable candidate for future-generation mobile communication systems that can be used with single-rate or multirate filters. It can also be used in combination with other PAPR reduction techniques. F-OFDM with PTS technique requires a smaller number of IFFT operations than F-OFDM with SLM. The result obtained from my present investigations reveals that F-OFDM with the PTS technique has 4.3 dB less PAPR than that of OFDM at the cost of marginal increase in the BER value.

Keywords: *Filtered Orthogonal Frequency Division Multiplexing, Partial Transmit Sequence, Selective Mapping Method, Out of Band leakage, Peak to Average Power Ratio, Spectral Efficiency.*

Introduction

While the fifth generation (5G) wireless communication is focused to provide services for massive machine type communication (mMTC), ultra reliable low latency (uRLLC), and enhanced mobile broadband (eMBB) (Lien et al., 2017). The next generation (6G) wireless communication system will be focused for connecting everything, provide support for mission critical applications, multimedia applications such as high-fidelity holograms, tactile or haptic based applications, immersive reality, etc. (Yadav, 2022a). In order to fulfill these requirements, it requires higher system bandwidth, new radio waveforms, new physical layer technique, enhanced higher layer capabilities, etc. (Rateb & Labana, 2019). 6G wireless communications have attracted much attention from both industry and academia. Compared with 5G, 6G will have: wider frequency bandwidth, higher transmission rate, higher spectrum efficiency, greater connection capacity, shorter delay, broader coverage, robust anti-interference capability to satisfy various network requirements (Tataria et al., 2021).

Materials and Methods

6G will have bandwidth in the range of 10-100 GHz, peak data rate greater than 1 Tbps, spectral efficiency equal to 7 bps/Hz, latency close to 1 ms /25 μs, mobility up to 1000 km/h, connection density in the range of 10^7 devices/ km^2, positioning accuracy near to 10 cm and wavelength in the sub mm range, etc. (Yadav, 2022b). The 6G mobile communication will revolutionize technology in the areas of new media (Holographic), new services (Teleport), and new infrastructures (Trust) (Jiang et al., 2021). In order to generate a large number of innovative applications and intelligent services, 6G will have super ultra-reliable low latency with extended reality communications (Yadav, 2022c). The 6G with transformative technologies will revolutionize concept of communication systems from connected things to connected intelligence. In order to satisfy these service requirements, both industry and academia have started to move their research beyond 5G and have started exploring about the 6G. It is predicted that 6G will be established on ubiquitous artificial intelligence (AI) to achieve data-driven machine learning (ML) solutions. But due to privacy concern use of traditional ML that is based on centralized processing is discouraged and the focus is to use federated learning (FL) that is an emerging decentralized ML solution for 6G implementations (Liu et al., 2020). In my present paper, investigations have been carried out to suggest a suitable waveform candidate that is optimally feasible for 5G and beyond applications (Yadav, 2023). OFDM was proposed by third generation partnership project (3GPP) for long term evolution (LTE) and LTE advanced (LTE-A) as a multicarrier communication system. It was used in 4G mobile communication system which is robust to the channel impairments and has high data rate transmission capability. But it is not suitable to be used in 5G and beyond systems because of having high PAPR as high PAPR causes power amplifiers to operate in the non-linear region and produces distortions in the output. Due to use of cyclic prefix, its spectral efficiency is low and has high OOBE due to use of rectangular pulse shaping waveform. OFDM has strict synchronization requirement that is not possible for the next generation communication system because of huge number of data generated by the sensors used for IoT and other industrial applications.

The F-OFDM waveform is a promising waveform candidate for the future generation wireless communication systems. Its performance in terms of PAPR, spectral efficiency, OOBE, etc. are better than that of the OFDM technique. It does not require synchronization of the input data, cyclic prefix is used once in a subblock, not with each subcarrier that results in improved spectral efficiency. For pulse shaping, instead of rectangular pulse, soft truncating pulses like, raised cosine windows are used that reduces the OOBE. In order to reduce the cost and complexity of the systems instead of single rate filters, multirate filters can be used that makes it suitable for the low-cost narrow band IoT devices for 5G/6G applications (Han & Lee, 2005). The F-OFDM can be integrated with other PAPR reduction techniques like, selective mapping method (SLM) and partial transmit sequence (PTS). In the SLM technique, each subcarrier is multiplied by a complex signal having unique phase vector before IDFT operation (Wang, Ku, & Yang, 2010). N number of PAPR is generated and the lowest one is selected for transmission and information of the phase vector that has produced lowest PAPR, is sent to the receiver for detection of the signal as a side information. This additional data is an overhead on the system that reduces the data transmission rate. PTS is one of the efficient methods for reducing PAPR as it requires a smaller number of IDFT operations (Yang et al., 2006). In this the input data is first partitioned into subblocks and scrambling is applied to each subblocks rather than to each subcarrier as used in the SLM technique. With the use of SLM and PTS technique along with F-OFDM, there is a significant reduction in the peak to average power ratio and OOBE at the cost of marginal increase in the system complexity, with very marginal degradation in the BER performance.

Literature Review

Literature review reveals that investigations on suitable waveform candidate for future generation wireless communication applications have been done by many researchers. For example, in Guneser, Sahab & Seker (2022) performance analysis of filter bank multicarrier (FBMC), filtered OFDM (F-OFDM) and universal filtered multicarrier (UFMC) for fifth generation mobile communication has been studied. The researcher has compared its performance with that of cyclic prefixed OFDM (CP-OFDM) for bit error rate (BER), transmission rate, peak to average power ratio (PAPR), and power spectral density (PSD. In Kim et al., (2020) Singular Value Decomposition (SVD) based filtered OFDM (SF-OFDM) has been proposed. Their study reveals that SF-OFDM has reduced computational complexity than that of F-OFDM without restrictions on the filter length used in transmitter and receiver. The study further suggests that the problem of data distortion was mainly due to smaller filter length compared to the symbol duration. Investigations on multiband F-OFDM waveform has been reported in Zhu et al., (2029) for tunable 3 section distributed Bragg reflector laser direct modulator. It has been used for wavelength division multiplexing (WDM) based radio over fiber network for 64 QAM and above modulation format. The system reported can be used without RF power fading that is caused due to interplay between laser chirp and fiber dispersion.

In Yang, Chen & Du (2019) for the uplink asynchronous F-OFDM system, a multi user system interference and bit error rate has been studied. They have demonstrated that performance of F-OFDM system is subjected to filter parameters, cyclic prefix length, subcarrier spacing, and degree of asynchronization. Researchers have suggested that in order to get better spectral efficiency an optimization model that is based on theoretical analysis and that can configure suitable parameters may be used. In Chen et al. (2019) a downlink asynchronous F-OFDM systems has been investigated by establishing the structures of the interference and dividing the interference in two parts: inter-subband and influence of inner-subband interference. The researchers have verified the derivation results through simulations based on a closed form expressions for sub- interferences and its variance. Wireless resource virtualization and allocation algorithm has been proposed in Yu et al. (2020) for time division duplex F-OFDM system with multi user multiple input multiple output (MIMO). Using resource virtualization technology, they have obtained the average link rate and equivalent capacity. In their investigations, they have decomposed the existing problem into two new sub-problems, first one for resource allocation at physical layer and the second one for traffic flows access problem at MAC layer. Uplink interference has been analyzed for the filtered OFDM system for asynchronous signals in Chen et al. (2020). In their study, they have derived expressions for sub-interferences and its variance and validated result through simulations. In Loulou et al. (2020) for a spectrally efficient narrowband OFDM transmitter, a low complexity solution based on the use of lookup tables have been proposed. It is mostly suitable for narrowband low power IoT and massive machine type systems that require only memory units with reduced hardware. For improvement in the spectral efficiency for 5G technology joint trail from Docomo and Huawei have been done in Wang et al. (2017). They have reported their results for sparse code multiple access, polar coding and filtered OFDM techniques. Review on FBMC, GFDM, UFMC and F-OFDM has been reported in Shaiek et al. (2019). These waveforms are a suitable candidate for 5G and beyond mobile communication systems. Form their study they have revealed that the techniques investigated have better spectral efficiency and low PAPR than that of the OFDM.

In Zhang et al., (2018) theoretical study on suitable waveform candidates for 5G and beyond and its effect of nonlinear distortion have been reported. In their study, they have developed an analytical expression for nonlinear distortion and symbol error rate and have demonstrated that the result obtained through analytical analysis were almost equal with that of the simulated results. For asynchronous input signal F-OFDM system has been analyzed in Al-Jawhar et al. (2021) and studied its effect on adjacent-carrier interference (ACI), inter carrier interference (ICI) and inter symbol interference (ISI). In their study, they have proposed a compensation matrix along with an algorithm for channel equalization and performance optimization of a subcarrier in a given subband. Using partial transmit sequence (PTS) with F-OFDM technique, effect on PAPR, BER, OOBE and computational complexities have been reported in Yadav & Bera (2015) and have shown that with the PTS F-OFDM technique, there is more than 10 dB reduction in OOBE and 4.3 dB reduction in PAPR with similar BER performance with moderate increase in computational complexities.

Filtered-Orthogonal Frequency Division Multiplexing

F-OFDM is one of the suitable waveforms for the next generation mobile communication systems (Yu et al., 2020). Here, the signal is filtered in time domain in order to reduce attenuation of side lobes and mutual interference. In this system, the allocated bandwidth is divided into k subbands and then each subband signal is filtered with the help of subband filter before transmitting. The subband filter is used to reduce inter subband interference that ultimately reduces sidelobe area and out of band leakage (OOB). Operation of filtered OFDM system is described by (1).

$$x(t)=\sum_{k=-\infty}^{\infty} \delta_n(t-kT) = \sum_{k=-\infty}^{\infty}\left[\sum_{k=0}^{1} a_{k,n}\, e^{j2\pi n\Delta f(t-kT)}\right] \otimes h(t-kT) \tag{1}$$

Figure 1 exhibits the block diagram of F- OFDM systems.

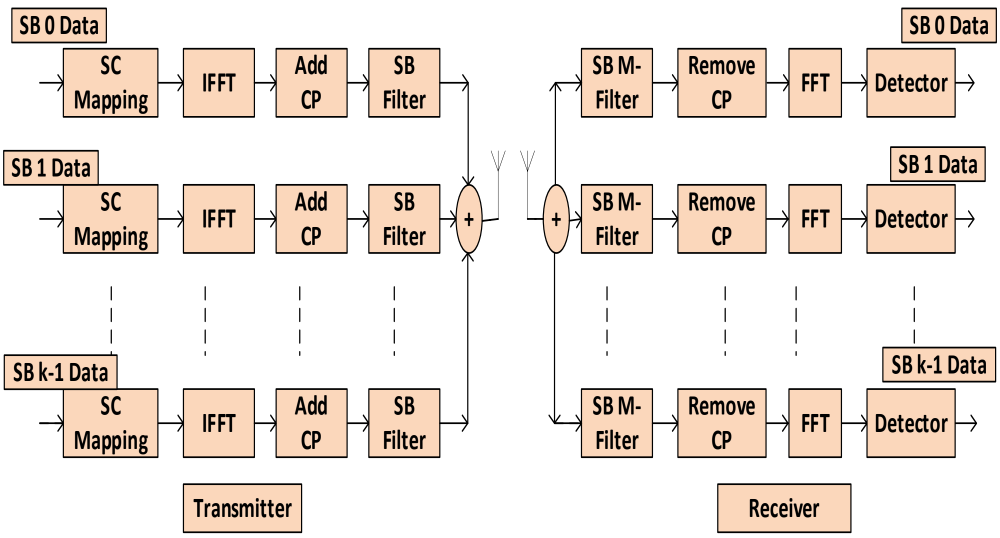

Figure 1. Filtered OFDM Transceiver

Here, k is the number of subbands, ⊗ is the symbol for circular convolution, and N is the length of FFT/ IFFT. Information at the rate of R bits/s is received at the input in groups of log_2M bits and after mapping it is sent to the next block at the of R/log_2M symbols/second. After dispreading the signal in time domain using IFFT of length N, cyclic prefix is added and filtered with the help of subband filtering. The combined signal is transmitted through the

AWGN channel and received at the receiver unit for further processing and retrieving the transmitted signal.

It uses low dimension full size IDFT equal to the size of one subband and spreads the signal across the full baseband bandwidth. But due to the up-sampling operation, it reduces the signal bandwidth to 1/K times, that creates (K-1) image signals in the adjacent bands. Frequency response of filter and channel are given by (2), (3) and (4), where, m_k, r_k and p_k are the subband filters at transmitter, receiver and channel respectively.

$$d_k = F^H . \left[m_k, o_{1\,X\,(N-L_F)}\right]^T \qquad (2)$$

$$h_k = F^H . \left[p_k, o_{1\,X\,(N-L_{CH,k})}\right]^T \qquad (3)$$

$$p_k = F^H . \left[r_k, o_{1\,X\,(N-L_F)}\right]^T \qquad (4)$$

Where d_k, p_k and h_k are the frequency response of N dimension subband filters at transmitter, receiver and channel respectively. Multirate systems generates higher inter subband interference (IsubBI) as compared to ACI, ISI and ICI. Zero Forced (ZF) algorithm has been used to cancel IsubBI. The received signal of the k-th subband with multirate sampling is given by (5) and (6).

$$x_k^{MR} = \sum_{l=1}^{K} \frac{1}{pl} Z^H \; Y^H \; T \; C_k \; B_l \; A_l \; RYZ \; E_l \; s_l + z_k \qquad (5)$$

$$x_k^{MR} = \sum_{l=1}^{K} \sum_{m=1}^{K} G_k^{[m]} \; H_k^{[m]} \; F_l^{[m]} \; E_l \; s_l + z_k \qquad (6)$$

Here, Y is the up-sampling matrix with a factor of K and Z is the normalized matrix of M-point IFFT. The desired signal is expressed by (7) and the inter subband interference is represented by (8).

$$x_{DES,\;k}^{MR} = \sum_{l=1}^{K} G_k^{[m]} \; H_k^{[m]} \; F_l^{[m]} \; E_k \; s_k \qquad (7)$$

$$x_{ISubBI,k}^{MR} = \sum_{l=1,l\neq k}^{K} \sum_{m=1}^{K} G_k^{[m]} \; H_k^{[m]} \; F_l^{[m]} \; E_l \; s_l \qquad (8)$$

Performance analysis has been performed using following parameters mathematical modelling and Matlab simulations: FFT length- 512, number of resource blocks-24, number of subcarriers per resource block-10, number of subcarriers-240, cyclic prefix length in a sample-50, baseband signal-16 QAM, SNR- 20 dB, tone offset (Excess Bandwidth)- 2.5, and filter length-1025. The PAPR obtained through mathematical modeling and Matlab simulation is reflected in in figure 2.

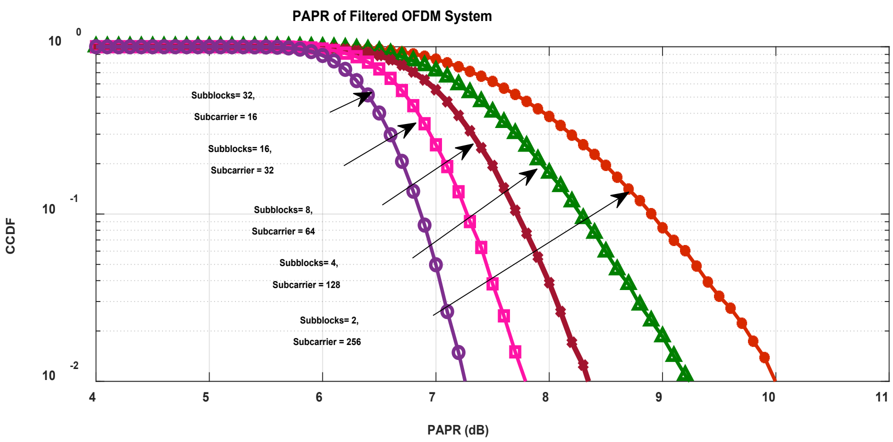

Figure 2. PAPR of F-OFDM System

Selective Mapping Method With Filtered OFDM

Selective mapping method when used with F-OFDM reduces PAPR significantly. In this the F-OFDM output is given to SLM after converting it from serial to parallel form and then each subcarrier is multiplied with a complex signal of different phase vector. Then N-point IDFT/IFFT is taken and subsequently its PAPR is calculated. The phase vector which produces the lowest value of PAPR is transmitted. For detecting the signal, information of the phase vector responsible for producing minimum PAPR is also transmitted along with signal as described in (9), (10) and (11). But this information is an overhead and can be tolerated at the cost of low PAPR value obtained. The operation of SLM technique along with F-OFDM is shown in figure 3.

$$Q^u = [Q_0^u, Q_1^u, \dots\dots Q_{N-1}^u]^T \qquad (9)$$

Where $Q_n^u = e^{j\theta_n^u}$, $\theta_n^u \in [0, 2\pi]$, n = 0, 1, ……., M-1, and u = 1, 2,……N-1.

$$M^u = [M^u[0],\ M^u[1], \dots\dots . . M^u[N-1]]^T \quad (10)$$

As mentioned from the N data vectors, Wmin = W_u^N which has the lowest PAPR is selected for transmission and represented by (17).

$$W = \underset{[u=1,2,\dots U]}{\arg\ \min} \left(\max_{n=0,1,\dots N-1} |\ W^u\ [n]| \right) \quad (11)$$

Information about the phase vector which has produced minimum PAPR is selected and transmitted to the receiver as side information. It requires N number of IFFT operation and $log_2 V$ bits of side information for each block of dataset.

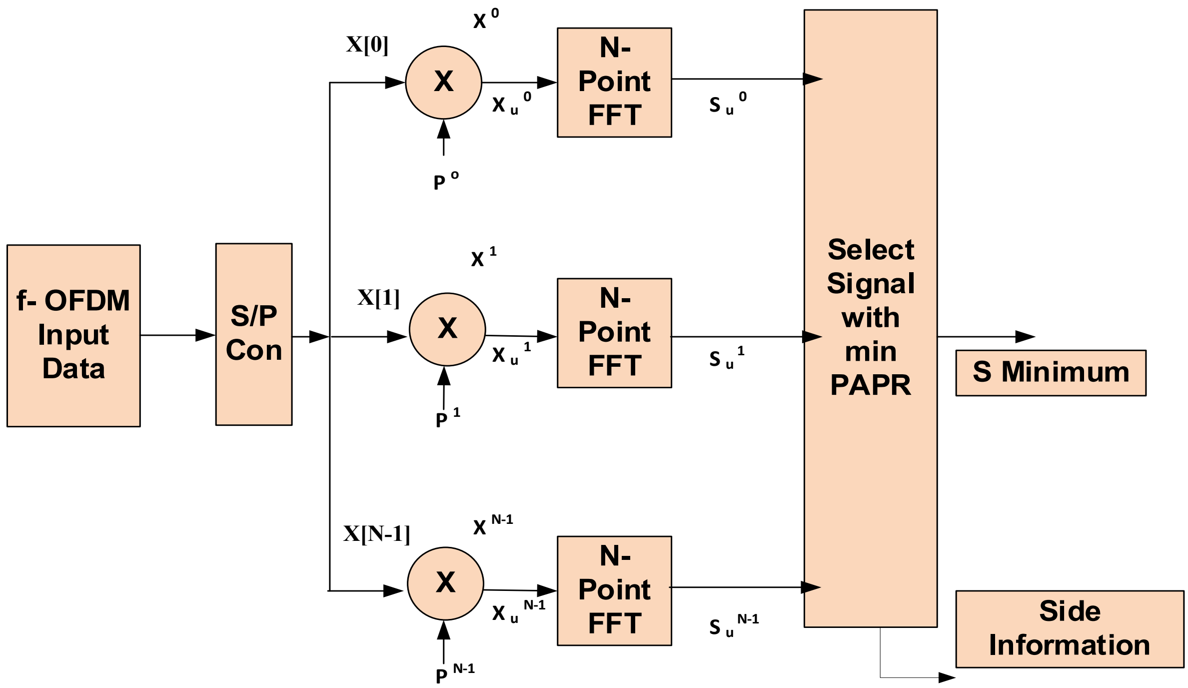

Figure 3. F-OFDM with SLM Transmitter

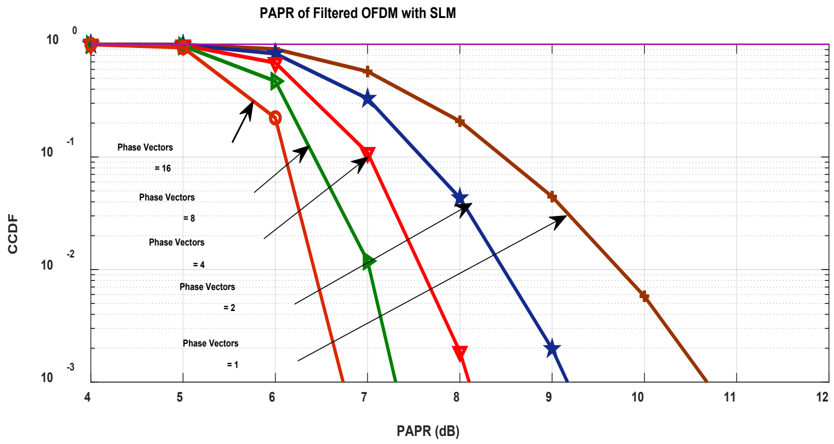

Figure 4. PAPR of F-OFDM with SLM

Figure 4 represents the PAPR of filtered OFDM used with SLM technique. It is evident from the figure that PAPR decreases with increase in number of phase vectors.

Partial Transmit Sequence with Filtered OFDM

Partial transmit sequence (PTS) when used with F-OFDM as shown in figure 5. It enhances its performance in terms of PAPR, BER and OOBE, etc. Further, PTS has low computational complexity than SLM technique as a single-phase vector is used for a group of subcarriers/subblocks. This reduces the number of IDFT/IFFT operations and subsequently is less computationally complex. It can be observed from figure 5 that the data is first converted from serial to parallel and then partitioned into N number of subblocks as reflected by (12).

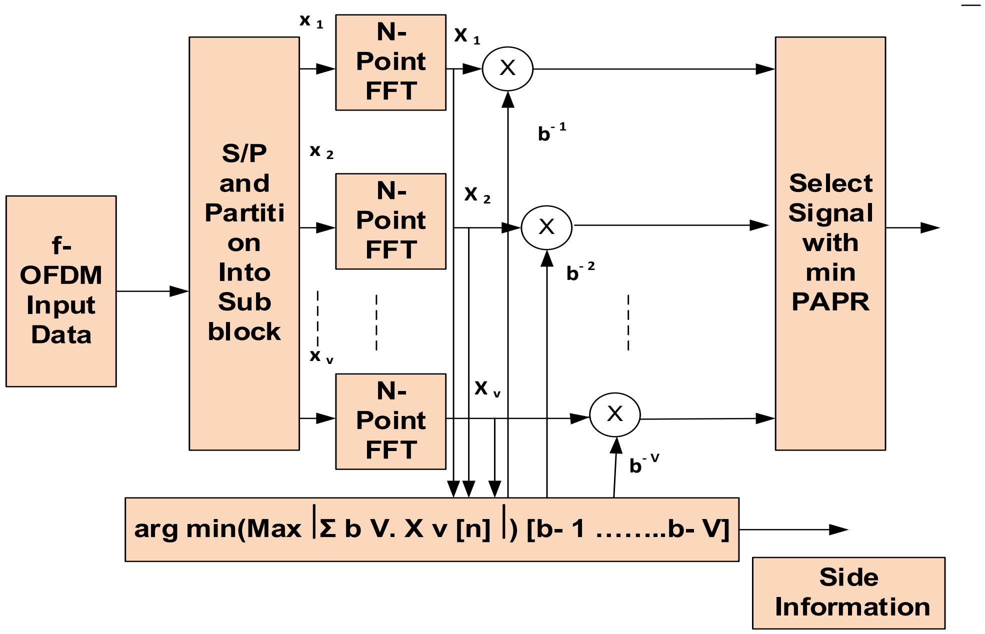

Figure 5. F-OFDM with PTS Transmitter

$$x = [x_0, x_1, x_2, x_3, \ldots \ldots .. x_N]^T \quad (12)$$

Where x_n is the nth subblock and size of all subblocks are same. After partitioning of subblock, each subblock is multiplied with unique complex phase vector that is given by $p^n = e^{jpn}$ as shown in (13) where, n =1, 2, …N.

$$x = \mathrm{IFFT}\left\{\sum_{n=1}^{N} p^n X^n\right\} = \sum_{v=1}^{v} p^n . \mathrm{IFFT}\{X^n\}$$

$$= \sum_{n=1}^{N} p^n x^n \quad (13)$$

Where x^n represents the PTS and phase vector is selected to minimize the PAPR. The signal in time domain that gives the lowest PAPR is shown in (14).

$$q = \sum_{v=1}^{v} b^{-n} x^n \quad (14)$$

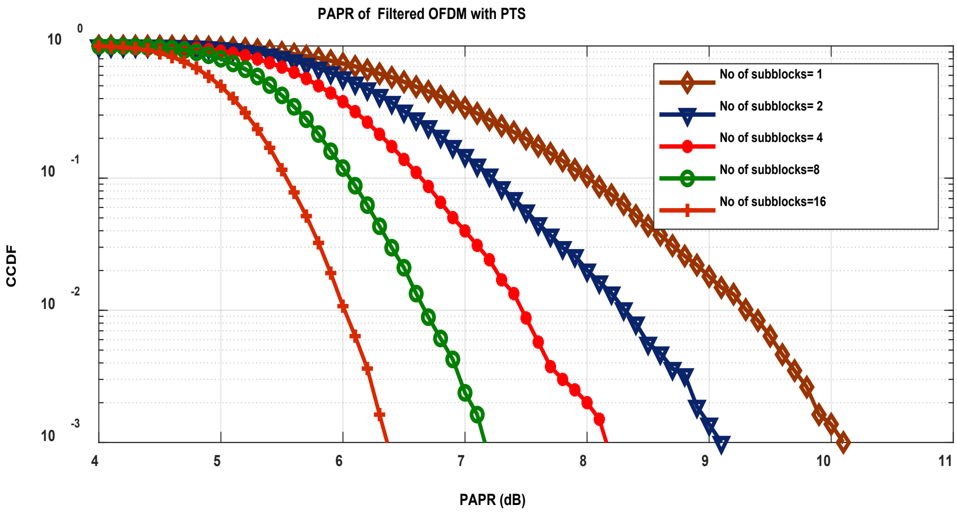

Figure 6. PAPR of F-OFDM with PTS

The number of IDFT/IFFT required for the PTS technique is N having $\log_2 X^n$ length of side information. The value of PAPR obtained also depends upon the way subblocks are partitioned along with number of phase vector and subblocks. In this work, the subblocks have been partitioned based on pseudo-random method, 4000 subblocks and 16 QAM baseband signal have been used in the investigation. Figure 6 reflects the PAPR value obtained through mathematical modeling and Matlab simulations with different number of subblocks. It is evident form figure 6 that the value of PAPR decreases with increase in number of subblocks.

Results and Discussion

PAPR and BER values for different techniques under study is depicted in Table 1. The study reveals that at 10^{-4} of CCDF, F-OFDM with PTS has the lowest PAPR value and at 30 dB of signal to noise ratio OFDM has the lowest bit error rate. At the cost of marginal increase in the BER value, F-OFDM with PTS technique has 4.3 dB less PAPR than that of OFDM.

Power Spectral Density

OFDM has the highest out of band leakage (OOB) power leakage due to use of rectangular pulse shaping. As evident from figure 7, the F-OFDM with PTS technique gives the lowest OOBE than other techniques under study.

Table 1. BER and PAPR Performance Comparison

Modulation Technique	CCDF	PAPR (dB)	SNR (dB)	BER
OFDM	10^{-4}	10.7	30	0.020
F-OFDM	10^{-4}	7.7	30	0.025
F-OFDM with SLM	10^{-4}	7.0	30	0.030
F-OFDM with PTS	10^{-4}	6.4	30	0.035

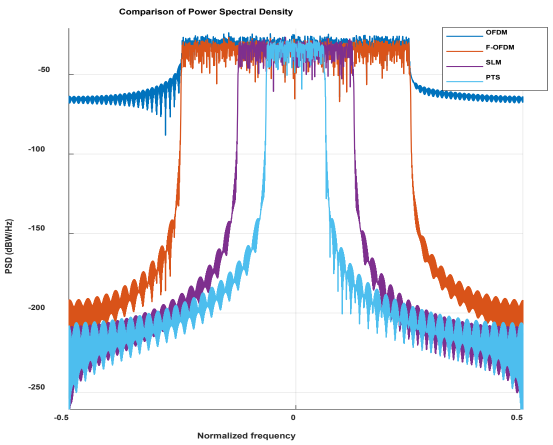

Figure 7. Comparision of Power Spectral Density

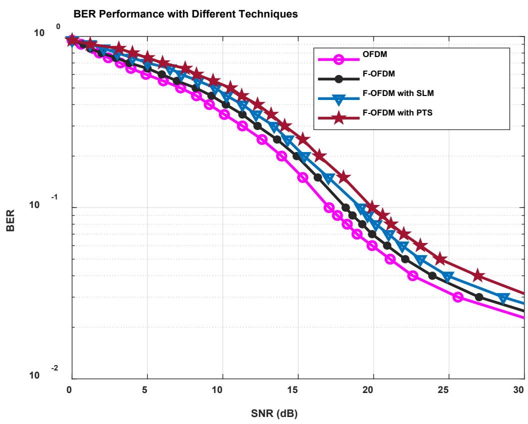

Figure 8. BER Performance with Different Techniques

Bit Error Rate

Figure 8 shows the value of bit error rate for OFDM, F- OFDM, F- OFDM with SLM and F-OFDM with PTS techniques. Comparatively OFDM has marginal lower BER than other techniques.

Peak to Average Power Ratio

One of the major drawbacks of OFDM used in 4G is that it has high value of PAPR. High PAPR causes power amplifiers to operate in the non-linear region and produces distortions in the output. From figure 9, it can be revealed that F-OFDM with PTS techniques has the lowest PAPR than the other techniques and is more suitable for the future generations of communication systems.

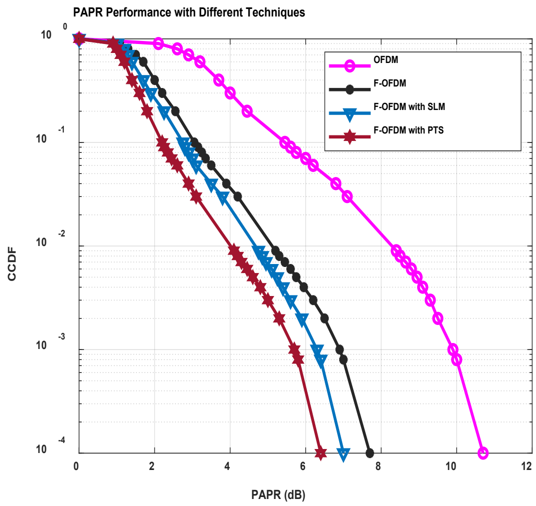

Figure 9. PAPR Performance with Different Techniques

Conclusion

Investigations on suitable waveform candidate for future generations mobile communication have been reported in this paper. It reveals that out of the OFDM, F- OFDM, F- OFDM with SLM and F- OFDM with PTS techniques, F-OFDM with PTS technique has comparatively better performance in terms of peak to average power and out of band power emission at the cost of slight increase in bit error rate and computational complexities. F- OFDM with PTS technique require less number of IDFT/IFFT operations than F- OFDM with SLM. The result obtained from my present investigations reveals that F-OFDM with the PTS technique at 10^{-4} CCDF has 4.3 dB less

PAPR than that of OFDM at the cost of 0.015 increase in the BER value at 30 dB SNR.

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