Performance Analysis of FBMC and OFDM with MIMO for Wireless Communications

Yedukondalu Kamatham and Sushmitha Pollamoni

Abstract In recent years, wireless communication systems are evolved with incredible technological advances which will change the way people communicate and interact. Fifth-generation (5G) wireless communications face a variety of challenges that supports large-scale heterogeneous networks. For supporting 5G communication networks, multicarrier modulations with several transmit and receive antennas have been developed. In this context, this research carries work that deals with comparative analysis of two systems, i.e., multiple-input multiple-output—orthogonal frequency division multiplexing (MIMO-OFDM), filter bank multicarrier (MIMO-FBMC) with different modulation techniques. The power spectral density (PSD) of OFDM, FBMC, MIMO-OFDM, and MIMO-FBMC is estimated and compared. It is found that the spectral efficiency (SE) of FBMC and MIMO-FBMC is more than OFDM and MIMO-OFDM. The bit error rate (BER) and peak-to-average power ratio (PAPR) are also analyzed. The PAPR and BER performance of FBMC is better than OFDM. But the PAPR of MIMO-FBMC is no longer better than MIMO-OFDM. Hence for MIMO wireless communications, OFDM is a better choice, whereas for non-MIMO communications systems FBMC is a good choice.

Keywords MIMO · OFDM · FBMC · PAPR · BER

1 Introduction

In wireless communications (WC), orthogonal frequency division multiplexing (OFDM) is considered as the most privileged technique which dominates the digital broadband communications. The principle behind OFDM is to divide the available spectrum bandwidth into sub-bands with less complex transceiver designs [1]. With many advantages, OFDM suffers from several inadequacies and unsatisfactory requirements for 5GWC. According to 3GPP, the 5G is mostly implemented in massive machine-type communications (mMTC) with the latency of 10 s, ultra

Y. Kamatham (✉) · S. Pollamoni
Department of Electronics and Communication Engineering, CVR College of Engineering, Hyderabad, India

reliable, and low latency communication (URLCC) and enhanced mobile broadband (eMBB) with high capacity (500 kmph) of 4 ms latency [2, 3]. For satisfying the future requirements, several modulation candidates are competing in the physical layer to prove the best favorable performer for the next generation of communications systems. The contenders are filter bank multicarrier (FBMC), OFDM, universal filtered multicarrier (UFMC), and generalized frequency division multiplexing (GFDM) [4]. For deciding, whether the candidate is insignificant or not, the following key features are considered and every feature is taken into account with various weighing factors for overall evaluation and decisions. The key possessions are peak-to-average power ratio (PAPR), power spectral density (PSD), spectral efficiency (SE), the design complexity of transceiver, and multiple access interference (MAI) [5].

Multicarrier modulation (MCM) schemes are used for providing SE. OFDM, FBMC, UFMC, and GFDM are examples of MCM systems. The mandate for gigantic data rates and traffic density is enhancing day to day. To gain the attention of this multiple-input multiple-output (MIMO) systems are developed and proven that MIMO is better for problem-solving of traffic capacity in wireless communications [6]. The MIMO is used for multipath transmission with multiple transceiver antennas.

In OFDM, many subcarriers are orthogonal to each other such that each subcarrier overlaps without interference and a guard band is not required for separation of subcarriers. The effect of multipath is encountered by the addition of cyclic prefix (CP) to OFDM symbol and circular convolution takes place which eliminates the inter symbol interference (ISI) due to multipath fading [7]. Due to the addition of the CP, some amount of data is added for each OFDM symbol which leads to a reduction in SE. OFDM also suffers from high PAPR which leads to high power amplifier to operate in the nonlinear region and increases harmonic distortion with out-of-band radiation (OBR) (increase in the spectrum) and in-band radiation (IBR). The harmonic distortion also leads to a reduction in SE. To overcome this problem in OFDM-MCM, an alternate technique is introduced, i.e., FBMC, which is used to provide more SE and to maintain a high data rate. In FBMC, the data of each subcarrier is shaped with the use of a specified filter of well-localized in both time and frequency domain, side lobes also reduced by this reshaping when compared with OFDM. OBR is also controlled and usage of cyclic prefix is not mandatory in FBMC [8] such that more data can be transmitted.

This research work deals with the comparison of SE of FBMC and OFDM. The FBMC and OFDM are combined with MIMO to increase the capacity (or) data rate of the communications with less system complexity. For the estimation of bit error rate (BER), the minimum Ellucian distance method is used. The PAPR and BER are analyzed for both OFDM and FBMC.

The remainder of the paper is followed as: Section 2 deals with system models of OFDM and FBMC. Section 3 presents a brief comparison of OFDM and FBMC with simulation results. Section 4 provides a comparison of MIMO-OFDM and MIMO-FBMC with simulation results. Section 5 describes the discussion on results obtained in Sects. 3 and 4 and in Sect. 6 conclusions are presented.

2 A System Model for OFDM and FBMC

2.1 OFDM

In the OFDM system, the serial bit stream is modulated with quadrature amplitude modulation (QAM) to form N parallel bit streams such that ith parallel bitstream is represented as $s_i(t)$.

$$s_i(t) = a_i g(t) \cos(2\pi f_i t) b_i g(t) \sin(2\pi f_i t) \tag{1}$$

Then $D_i = a_i + b_i$ represents ith constellation symbols and $f_i = f_c + \Delta f$ is the carrier frequency of the ith subcarrier, where a_i represents a real part of complex symbols, b_i is the imaginary part of complex symbols, and Δf is the frequency separation between two subcarriers. The OFDM symbol is represented as

$$s(t) = \sum_{i=0}^{N-1} s_i(t) \tag{2}$$

where the complex envelope of the OFDM system is represented as

$$d(t) = \sum_{i=0}^{N-1} D_i g(t) e^{j2\pi \Delta f t} \tag{3}$$

The $d(m)$ sampling sequence of $d(t)$ is obtained from a period of 0 to T [8, 9].

$$d(m) = \sum_{i=0}^{N-1} D_i g(t) e^{j2\pi \Delta f. \frac{mT}{N}} \tag{4}$$

By the above equation, it proves that the OFDM symbol $d(m)$ is utilizing the inverse fast Fourier transform (IFFT). The OFDM transmitter structure is shown in Fig. 1.
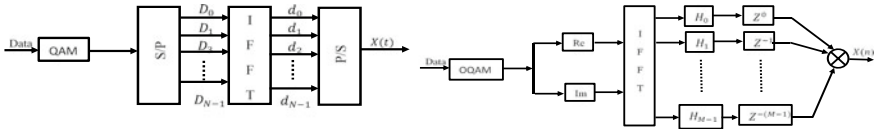
Fig. 1 Transmitter of OFDM and FBMC

2.2 FBMC

In the FBMC, the complex signal is modulated with an offset QAM (OQAM). Whether the complex signal with the real or imaginary part is interleaved, a double sequence length appears.

$$X_i = a_i = D_{i-\text{real}} \quad \text{and} \quad X_{i+1} = b_i = D_{i-\text{imag}} \tag{5}$$

In FBMC, the PHYDYAS [8] filter is used with an overlapping factor of $K = 2$, 3, 4. Such that the frequency response of the filter with M subcarriers is represented as

$$h_{n+1} = 1 - 2H_1 \cos\left(\frac{2\pi n}{KM}\right) + 2H_2 \cos\left(\frac{2\pi 2n}{KM}\right) - 2H_3 \cos\left(\frac{2\pi 3n}{KM}\right) \tag{6}$$

$$1 < n < KM - 1$$

The filter impulse response is with length $L = M * K$ and the sequence of coefficients h_i, i.e., into L length sequence, the data is filtered.

$$y(n) = \sum_{i=0}^{L-1} h_i x(n-i) \tag{7}$$

where $y(n)$ is filtered data in one group. In the frequency domain, the impulse response is represented as

$$H(f) = \sum_{i=0}^{L-1} h_i e^{-j2\pi i f}$$

The filter impulse response is represented as

$$H(Z) = \sum_{i=0}^{M-1} H_p Z^{-p}(Z^M) \tag{8}$$

where

$$H_p(Z^M) = \sum_{k=0}^{K-1} h_{kM+p} Z^{-kM} \qquad (9)$$

3 Comparison of OFDM and FBMC Simulation Results

3.1 OFDM

In OFDM, the input bitstream is modulated with the QAM technique such that each subcarrier is passed through IFFT with the orthogonality.

A CP is added and PSD of OFDM is estimated with different fast Fourier transform (FFT) sizes, i.e., FFT = 128, 256, 512, 1024. The PSD is calculated as

$$S_{xx}(\omega) = \lim_{T \to \infty} E\left[\left| \hat{x}(\omega) \right|^2 \right] \qquad (10)$$

where

$$\hat{x}(\omega) = \frac{1}{\sqrt{T}} \int_0^T x(t) e^{-i\omega t} \mathrm{d}t \qquad (11)$$

$x(t)$ is a signal with frequency content, $\hat{x}(\omega)$ is a signal with Fourier transform, $S_{xx}(\omega)$ is the PSD of the required signal. The PSD of OFDM with different FFT sizes is shown in Fig. 2 where spectral density (SD) defines the signal strength and successful transmission of bits in specified bandwidth over a time period. A modulated SD is efficient when the strength (middle part) is closer to the normalized frequency. For FFT size = 1024, the SE is good. Hence, higher FFT sizes are preferred for OFDM.

3.2 FBMC

FBMC is one of the MCM techniques. The input bitstream of FBMC is modulated with the OQAM technique such that each OQAM symbol is passed through FFT. Each FFT symbol is filtered with PHYDYAS filter with coefficients $K = 2, 3, 4$. For different values of K and various FFT sizes = 512 and 1024, the PSD of the FBMC system is shown in Fig. 3, and the comparison of FBMC is estimated with different values of filter coefficients K. By increasing the filter coefficient value, the
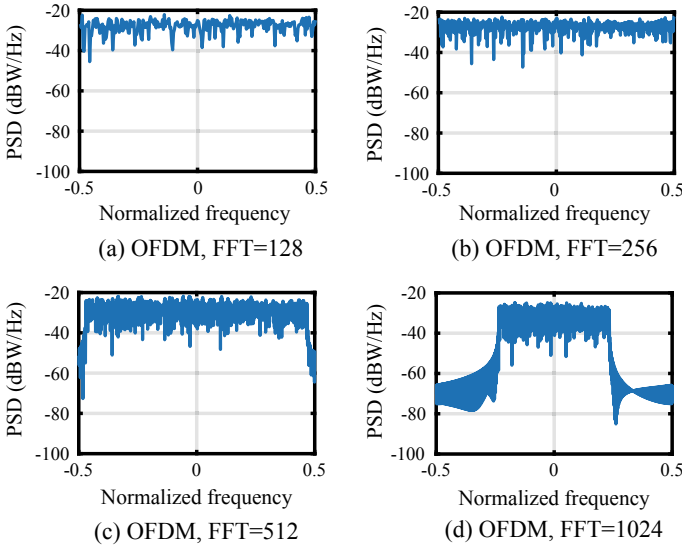
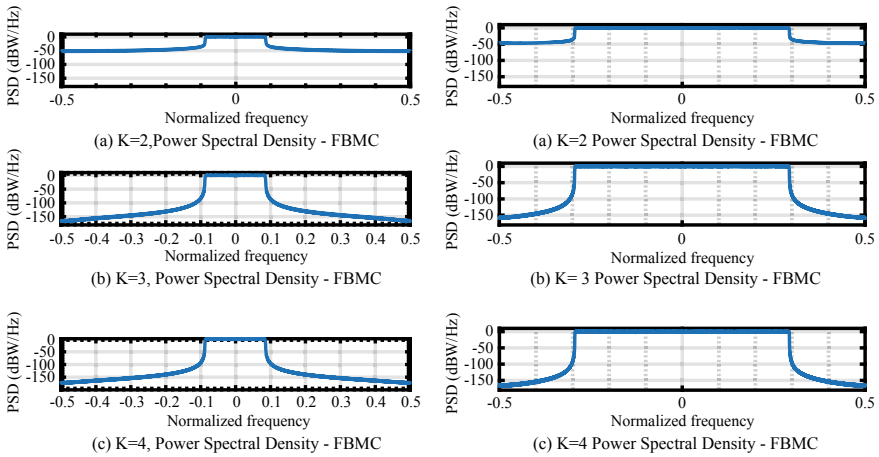Fig. 2 PSD of OFDM with different number of FFT sizes

Fig. 3 PSD of FBMC is compared with different k values and FFT sizes

PSD parameter in the y-axis gets decreases to the center of normalized frequency at $K = 4$, the spectrum is more difficult with the value (-180 to 180 dBW/Hz) of FFT size $= 512$ (Fig. 3). With increasing the FFT sizes, such that FFT size $= 512$ is good for better filter design and SE.

By comparing Figs. 2 and 3, the PSD of FBMC is less than OFDM. When compared with FFT size $= 1024$ in Figs. 2 and 3 the filter coefficients $K = 3$ and 4, the PSD is less in FBMC, i.e., the bandwidth efficiency is more in FBMC than

Fig. 4 Comparison BER of
OFDM and FBMC
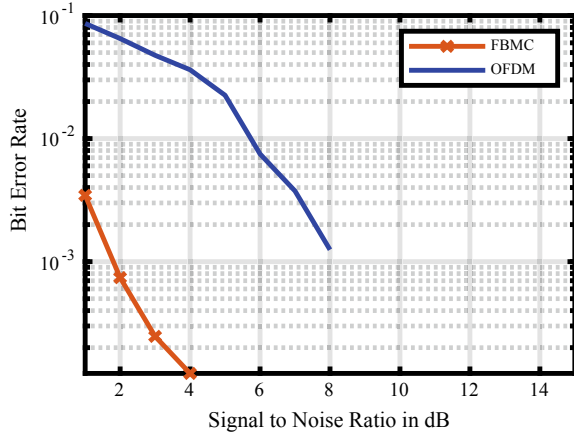
OFDM. The SE in OFDM decreases by the addition of side lobes which occupies more bandwidth. The addition of side lobes is eliminated in FBMC with the help of respective filters and usage of cyclic prefix is not mandatory. Therefore, the SE is more in FBMC than OFDM.

1. **Bit error rate (BER) performance**: BER is defined as the number of errors of bits occurred per unit time. BER is a function of $\frac{E_b}{N_0}$ and represented as

$$BER = \frac{1}{2} \text{erfc} \left(\sqrt{\frac{E_b}{N_0}} \right) \tag{12}$$

The BER of OFDM and FBMC is shown in Fig. 4. With increase in SNR, the BER performance is decreased. By comparing, the BER performance of OFDM is higher than the FBMC such that BER performance is better in FBMC than OFDM.

2. **PAPR analysis**: PAPR is defined as the ratio of instantaneous power to the signal average power.
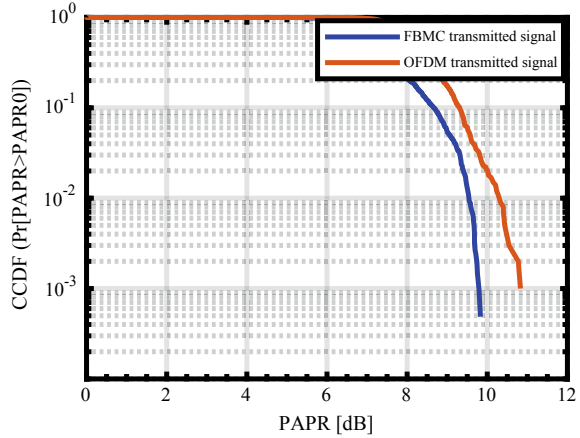
$$PAPR[x_n] = 10 \log_{10} \frac{\max |x_n|^2}{E\left[|x_n|^2\right]} \tag{13}$$

where $|x_n|$ is the signal peak power. The PAPR is evaluated by cumulative distributed function (CDF) within the threshold level.

$$F_z(z) = 1 - e^{-z} \tag{14}$$

The PAPR beyond the threshold level is expressed in terms of complementary cumulative distributed function (CCDF($\widetilde{F}_z(z)$)) as $\widetilde{F}_z(z) = 1 - (F_z(z))^n$.

Fig. 5 PAPR comparison of OFDM and FBMC

The estimation of PAPR performance for both OFDM and FBMC is shown in Fig. 5. At CCDF $= 10^{-2}$, the PAPR of FBMC is 9.5 dB and PAPR of OFDM 10.5 dB. The PAPR of FBMC is less than OFDM.

4 Comparison of MIMO-OFDM and MIMO-FBMC Simulation Results

4.1 MIMO

In MIMO systems, the multiple streams of data are transmitted through multiple antennas. These multiple streams are passed through a channel matrix which consists of $N_T N_R$ paths between N_T transmit antennas and N_R receive antennas. The receiver receives the signal vectors by multiple receivers and decodes the signal into the original information. A MIMO system is modeled as $Y = HX + n$.

Then Y is a received signal vector with a length of $Y = [y_1, y_2, \ldots, y_N]$ and X is a transmitted signal vector with a length of $X = [x_1, x_2, \ldots, x_N]$, H is a channel matrix with a length of $M \times N$ matrix and n is the noise vector.

1. **MIMO-OFDM**

To increase the high data rate, the OFDM signal is combined with MIMO of 2×2 such that PSD of MIMO-OFDM with different FFT sizes is shown in Fig. 6. With the increase in the FFT sizes the spectral density of MIMO-OFDM increases.

2. **MIMO-FBMC**

To increase the SE, the 2×2 MIMO system is combined with FBMC, and PSD of MIMO-FBMC is estimated with different values of K as shown in Fig. 8. With

Fig. 6 MIMO-OFDM with
FFT size 512 and 1024

(a) OFDM, fft size = 512

(b) OFDM, fft size = 1024
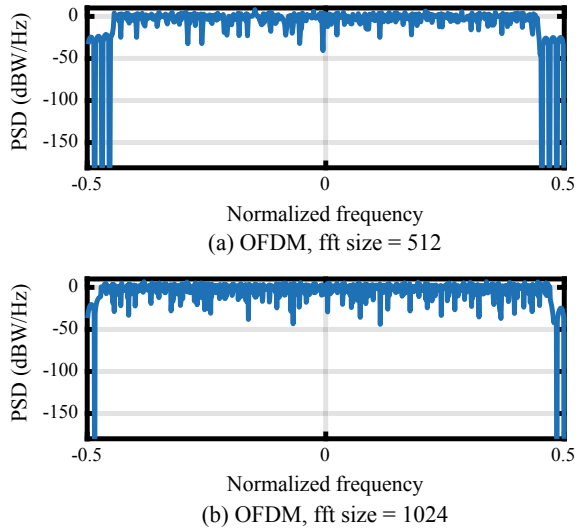
an increase in K value at FFT size = 512, 1024, the spectral density of FBMC also decreases. The SE decreases with an increase in FFT sizes rather than an increase in different K values. The SE for FFT = 512 is more efficient than FFT = 1024. By comparing Figs. 6 and 7 at FFT sizes = 512, 1024 the PSD of MIMO-FBMC is more. With an increase in K value, the spectral density decreases. The SE is more in MIMO-FBMC rather than in MIMO-OFDM because of the complex filter nature of the FBMC transmitter.
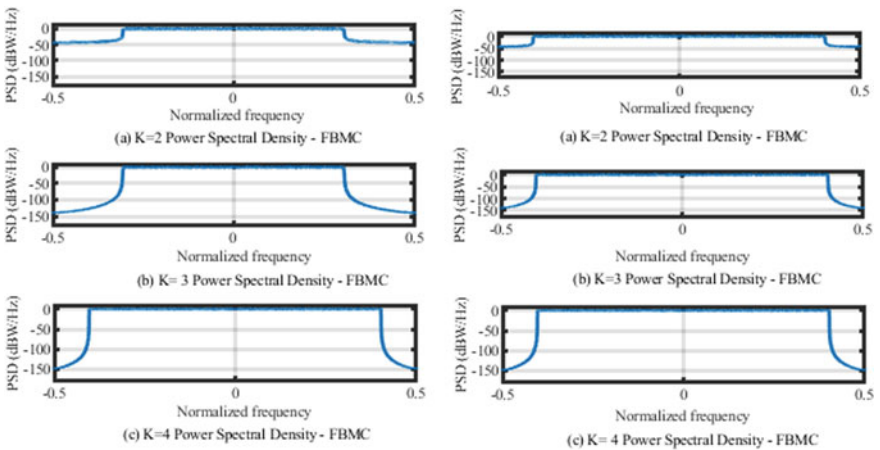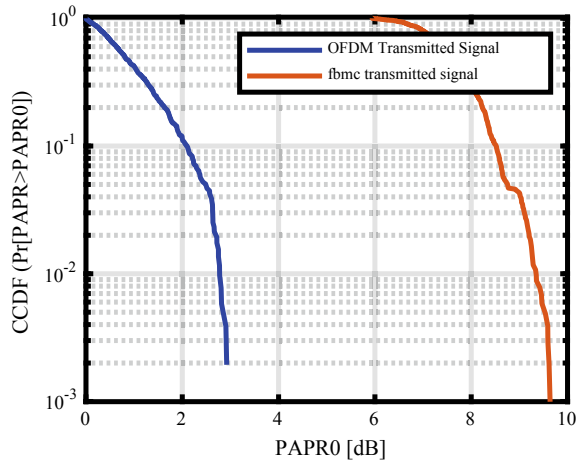
(a) K=2 Power Spectral Density - FBMC

(a) K=2 Power Spectral Density - FBMC

(b) K= 3 Power Spectral Density - FBMC

(b) K=3 Power Spectral Density - FBMC

(c) K=4 Power Spectral Density - FBMC

(c) K= 4 Power Spectral Density - FBMC

Fig. 7 Comparison of MIMO-FBMC with different k values and FFT sizes

Fig. 8 Comparison of PAPR
for MIMO-OFDM and
MIMO-FBMC

In Fig. 8, the comparison of PAPR performance for MIMO-OFDM and MIMO-FBMC. According to the comparison, the PAPR of MIMO-OFDM is less than the MIMO-FBMC.

5 Discussion on Simulation Results

OFDM system has been developed to decrease the ISI due to multipath fading. Reduction in SE is one of the major drawbacks of the OFDM system. To overcome the reduction of SE, the FBMC system has been developed. In FBMC, instead of using a cyclic prefix, the filter parameters are added such that side lobes of the signal decrease. The BER versus SNR is given in Table 1. BER of OFDM and FBMC is estimated and is less than the OFDM. The PAPR of OFDM, FBMC, MIMO-OFDM, and MIMO-FBMC is explained in detail in Sect. 3 such that the PAPR of FBMC is less when compared to OFDM. The PAPR of MIMO-OFDM is less compared with

Table 1 SNR versus BER

SNR	BER			
	OFDM BER	FBMC BER with varying K values		
		$K = 2$	$K = 3$	$K = 4$
1	0.08625	0.0035511	0.0036267	0.003582
2	0.065	0.0015388	0.0013298	0.00061759
3	0.0475	0.0008286	0.00036267	0.00024704
4	0.03625	0.000011837	0.00024178	0.00012352
5	0.0225	0	0	0

MIMO-FBMC. For the MIMO system, the PAPR of OFDM is better than FBMC according to the literature.

6 Conclusions

In this paper, the SE and PAPR of OFDM and FBMC are compared. Because of the addition of CP in OFDM, the SE gets reduced and due to high PAPR, the HPA enters nonlinear regions and leads to harmonics distortions includes OBR and IBR. To overcome these disadvantages, FBMC is developed. To gain spatial transmission, the MIMO system is combined with both OFDM and FBMC. The SE of MIMO-OFDM and MIMO-FBMC is estimated and compared such that SE for both FBMC and MIMO-FBMC is better than OFDM and MIMO-OFDM. The PAPR and BER of FBMC are better than OFDM, but PAPR of MIMO-FBMC is not better than MIMO-OFDM and also the transceiver design complexity is more in FBMC. Hence, in MIMO systems, OFDM can be used with an appropriate choice of companding techniques reported in the literature. But in non-MIMO wireless systems, FBMC is a better choice for PAPR and BER performance.

References

1. C. Bockelmann et al., Massive machine-type communications in 5G: physical and MAC-layer solutions. IEEE Commun. Mag. **54**(9), 59–65 (2016)
2. ITU-R Rec. ITU-R M. 2083-0, IMT Vision-Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond (2015)
3. P. Popovski et al., Wireless access in ultra-reliable low-latency communication (URLLC). IEEE Trans. Commun. **67**(8), 5783–5801 (2019)
4. R. Gerzaguet et al., The 5G candidate waveform race: a comparison of complexity and performance. EURASIP J. Wirel. Commun. Netw. **2017**(1), 1–14 (2017)
5. A. Husam, Z. Kollar, Complexity comparison of filter bank multicarrier transmitter schemes, in *2018, 11th International Symposium of Communication Systems, Networks and Digital Signal Processing (CSNDSP)* (2018)
6. R. Zakaria, D. Le Ruyet, A novel filter bank multicarrier scheme to mitigate the intrinsic interference: application to MIMO systems. IEEE Trans. Wireless Commun. **11**(3), 1112–1123 (2012)
7. I. Das, R.N. Shaw, S. Das, Location-based and multipath routing performance analysis for energy consumption in wireless sensor networks, in *Innovations in Electrical and Electronic Engineering. Lecture Notes in Electrical Engineering*, ed. by M. Favorskaya, S. Mekhilef, R. Pandey, N. Singh, vol. 661 (Springer, Singapore, 2021). https://doi.org/10.1007/978-981-15-4692-1_59

8. A. Ghassemi, T. Gulliver, Intercarrier interference reduction in OFDM systems using low complexity selective mapping. IEEE Trans. Commun. **57**(6), 1608–1611 (2009)
9. S. Shreyan, S. Rajarajan, Ch. Abhijit, Environment-adaptive concurrent companding and bias control for efficient power amplifier operation. IEEE Trans. Circuits **58**(3), 607–618 (2010)