A Review of 5G Modulation Schemes - OFDM, FBMC and UFMC

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Abstract—In this paper, we study the waveform design of 4G (based upon OFDM) and 5G. In recent years, FBMC has been promoted as a potential contender. Regardless of the fact that FBMC is better suited than OFDM in theory, practical considerations reveal many of FBMC's flaws. Filter Bank MultiCarrier, Universal Filtered Multi-Carrier, Generalized Frequency Division Multiplexing, and Filtered Orthogonal Frequency Division Multiplexing are examples of potential 5G waveforms.The most capable waveform contenders for the 5G air interface are reviewed in this paper. These waveforms are compared to OFDM, which is used in 4G, on parameters such as spectrum use efficiency, complexity, and robustness.

Index Terms—4G, 5G, FBMC, OFDM, PAPM, PAPR, multicarrier, spectral efficiency, UFMC

I. INTRODUCTION

Broadband data usage has increased at a rapid rate to keep up with cutting-edge technology and features in the form of smart phones that really can perform a variety of functions. Long Term Evolution (LTE) and the 4G cellular network provide high data bandwidth and are compatible with devices such as smartphones and tablets.OFDM is a waveform design principle that is well-known, well-studied, and widely used. OFDM is the basic signal format used by both 4G (LTE and its evolutions) and IEEE 802.11 (WiFi) for data transmission over the air. IoT (Internet of Things), M2X communications, Tactile Internet, WRAN (Wireless Regional Area Network), and Very large data rate wireless connectivity (up to 10Gb/s) are some of the unique features of 5G when compared to 4G. The OFDM method is insufficient for these applications. As a result, new approaches such as FBMC and UFMC are required.

OFDM is a special case of multi-carrier transmission. It divides the spectrum into subcarriers and uses guard bands to separate them. Due to the nature of the pulse shaping, these carriers overlap but are orthogonal. A Cyclic Prefix can be used to remove Inter-Symbol Interference (ISI). On the receiver side, a one-tap equaliser can be used. The benefits of a modulation scheme include the capacity for using signals with high data rates, the ability to provide minimal delay for long and concise data, the ability to exchange data quickly in the uplink and downlink, and the option of cost-effective broadcasting by reducing the on time of devices with limited data rates. Filter Bank Multi-Carrier (FBMC), Universal Filtered Multi-Carrier (UFMC), Generalized Frequency Division Multiplexing (GFDM), and Filtered OFDM (f-OFDM) are some of the 5G modulation methods. in this paper OFDM, FBMC and UFSC schemes are discussed.

II. ODFM

A. Overview

OFDM means Orthogonal Frequency Division Multiplexing. It is a multicarrier transmission technique that divides the available spectrum into multiple subcarriers and is modulated by a low data rate stream. It is a type of message waveform or modulation which provides several important advantages for data communications.

Many modern broad spectrum and high data rate wireless networks, such as Wi-Fi, cellular phones, and a number of others, uses OFDM. The reality of OFDM is that it uses a huge number of carriers, each holding low band rate data, signifies that it is extremely sensitive to specific fading, interruption, and spanning tree effects, as well as delivering a high level of spectral efficiency. The main idea behind OFDM is that, because low-rate modulations are less vulnerable to multipath, sending multiple low-rate streams in parallel is preferable over sending a single high-rate waveform. Data is carried by a large number of closely spaced orthogonal subcarriers. In wireless communications, OFDM is a promising technique for obtaining high data rates and preventing multipath fading.

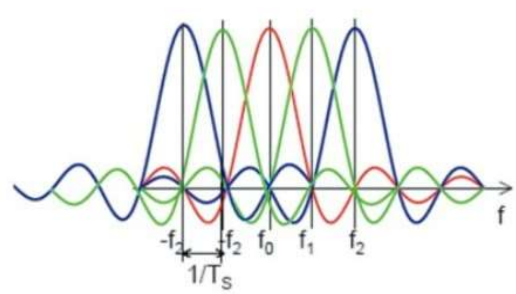

Fig. 1. OFDM WAVEFORM

all the Subcarriers are spaced by 1/Ts.

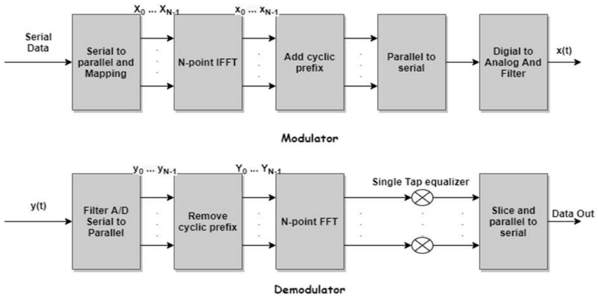

Fig. 2. OFDM Modulation Block-diagram

B. Key features of OFDM

- The information stream is carried by many carriers (known as subcarriers).
- The subcarriers are orthogonal to each other.
- Each symbol has a guard interval added to it to reduce channel delay spread and intersymbol interference.

C. Advantages

- Provides a transmission system that is spectrally efficient.
- Eliminate the requirement for an equaliser almost completely.
- Allows sub carriers to be densely packed and overlapped.
- Provides a transmission system that is spectrally efficient.
- Different modulation techniques are supported depending on the channel conditions.
- Can be digitally implemented using, fast andefficient signal processing.

D. Disadvantages

- PAPR is high when a number of subcarriers are modulated independently. The complexity of the ADC and DAC is likewise increased by high PAPR.
- Another disadvantage of OFDM is that it is vulnerable to carrier frequency drift and offset. Single-carrier systems are less sensitive than multi-carrier systems.

III. FBMC

A. Overview

FBMC refers to Filter Bank Multi-carrier. FBMC is a multicarrier modulation technique that has its origins in OFDM. It's a variation of OFDM that aims to address some of the drawbacks, however at the cost of increased signal processing. FBMC makes better use of available channel capacity and can deliver higher data rates within a given radio spectrum bandwidth, resulting in higher spectrum efficiency. FBMC filters each subcarrier individually and does not use cyclic prefixes. This scheme emphasises on spectrum efficiency.

Filter bank multicarrier tries to address some of the flaws in OFDM (orthogonal frequency division multiplexing) technology. Each subcarrier is filtered separately in FBMC. It uses a long-time filter with a very narrow band. OOB emissions are greatly reduced due to the usage of filters for each subcarrier. The first prototype filter will be designed in FBMC. Then, using frequency shifting, filters are designed for each subcarrier based on the prototype filter. Filter banks are the collective name for all the filters. The major distinction between OFDM and FBMC is that OFDM use a single rectangular filter for all subcarriers, whereas FBMC uses a separate filter for each subcarrier. Because FBMC does not employ a cyclic prefix, it has a better spectrum efficiency than OFDM. Because each filter is used for each subcarrier, FBMC has a high computational complexity. It is good for single-user transmission, but it is not efficient for multiple input multiple output transmission. It is also not an efficient solution for 5G communications due to these disadvantages.

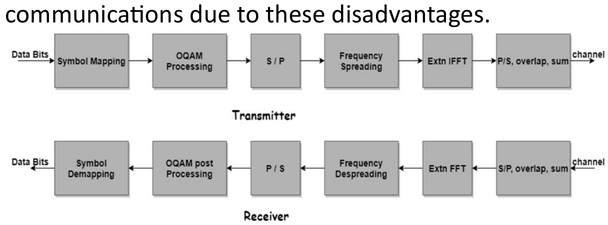

Fig. 3. FBMC Modulation Block-diagram

B. Advantages

- FBMC is able to provide a spectrum efficient and more selective system.
- The cyclic prefix, CP required for OFDM is not needed thereby freeing up more space for real data.
- Provide robust narrowband jammers

C. Disadvantages

- Because the use of MIMO with FBMC is so complicated, only a few systems have investigated at combining the two techniques.
- With FBMC, designing systems with a wide bandwidth and high dynamic range presents some significant RF development issues.
- FBMC is more sophisticated than OFDM because it imposes an overhead in the time domain due to overlapping symbols in the filter bank.

IV. UFMC

A. Overview

UFMC refers to Universal Filtered Multi-Carrier Modulation. UFMC, which is based on FBMC and OFDM, is one of the best and most unique multicarrier modulation techniques for 5G.

Filtered OFDM and FBMC modulations are combined in UFMC. Individual subcarriers are filtered in OFDM, and individual subcarriers are filtered in Filter Bank MultiCarrier (FBMC), and a group of subcarriers (sub bands) is filtered in UFMC. The filter length is split in half because of this subcarrier grouping (when compared with FBMC).

The total bandwidth is split into B sub-bands in UFMC. There are k sub-carriers in each sub-band.

Now data bits are given to each sub band. After that the data bits become parallel by the use of serial to parallel converter. Now the output of s/p converter is given to the symbol mapper. Symbol mapper assigns symbols to bits. The output of the symbol mapper is given to IFFT. Here the IIFT acts as a modulator. Designing modulators for each subcarrier is quite tough. The output of IFFT is serialized by parallel to the serial converter and that output will be filtered with pulse shaping filter of length L. The filter is a chebyshev filter. The output of each filter is added and the resulting signal is passed through the channel. The input data represented by X is converted to B sub-blocks. And each sub-block is passed through N point IFFT representing the matrix ‘V’. The output of IFFT will be serialized and passed through a filter representing the matrix
‘F’.

For the ith sub-band the data blocks are represented with Si,k,IFFT matrix with Vi,k and filter with Fi,k. The output of the filter bank is shown in equation 1.

$$X_k = \sum_{i=1}^{B} F_{i,k} \cdot V_{i,k} \cdot S_{i,k}$$

Fi,k represents Chebyshev filter

Vi,k represents IFFT to eplitz matrix

$$F_{i,k} = \frac{cos\{M \cosh^{-1}\left[\beta \cdot \cos(\frac{\pi k}{M})\right]\}}{\cos\left[M \cosh^{-1}(\beta)\right]}$$

$$k = 0,1,2,3,\ldots\ldots\ldots M-1$$

$$\beta = \cosh\left[\frac{1}{M} \cdot h^{-1(1_{0}\alpha)}\right], \alpha = 2,3,4$$

where α represents attenuation of side lobe

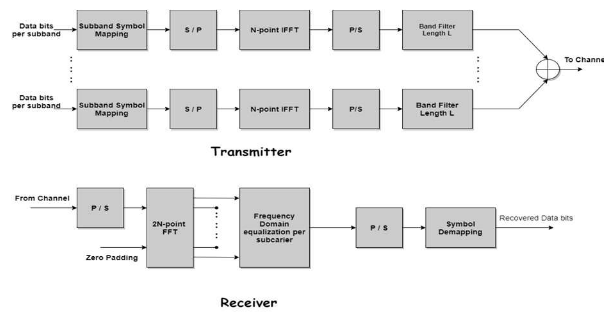

Fig. 4. UFMC Modulation Block-diagram

Figure 4 shows the block diagram of UFMC Receiver and Transmitter.

UFMC has more spectral efficiency compared to OFDM. There is no cyclic prefix insertion like in OFDM. There is no repetition of the same bits, therefore it utilizes all the allocated spectrum efficiently.

V. SIMULATION AND RESULTS *comparison of UFMC, FBMC and OFDM*

The UFMC, FBMC and F-OFDM are compared with the generic OFDM modulation scheme.

first comparison between FBMC and OFDM modulation schemes are shown.The simulation parameters for FBMC are listed in Table II.

number of FFT points	1024
Number of guard bands	212
Overlapping symbols (k)	3
Number of symbols	100
Bits Per Subcarrier	2
SNR (dB)	16

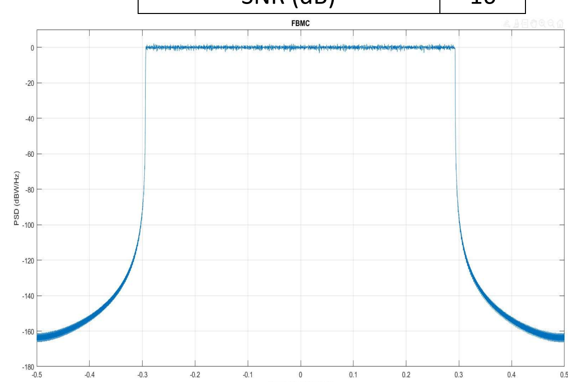

Fig. 5. The power spectral density of the FBMC transmit signal, K=3 overlapped symbol

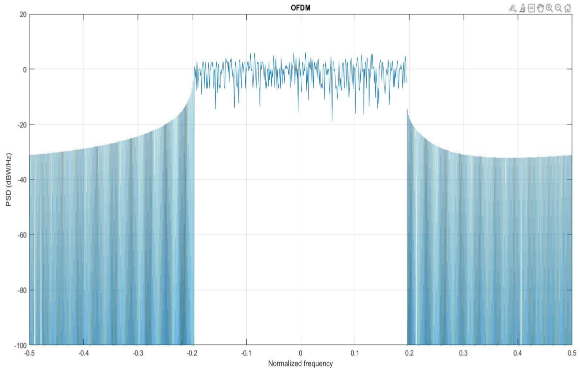

Fig. 6. The power spectral density of the FBMC transmit signal, number of FFT points= 1024

The plots of the Power Spectral Densities in Figures 5 and 6 show that FBMC has reduced side-lobes, allowing for better spectrum utilisation and spectral efficiency. The BER for the FBMC receiver with an overlapping factor of 3 is zero for 16 dB SNR.

now comparison between OFDM and UFMC modulation schemes are presented below. The simulation parameters for UFMC are shown in Table I. The OFDM uses the fully occupied band without cyclic prefix.

number of FFT points	512
Number of sub-bands	10
Sub-band size	20
Filter length	43
Bits Per Subcarrier	4
Side lobe attenuation	40
SNR (dB)	16
Sub-band Offset	156

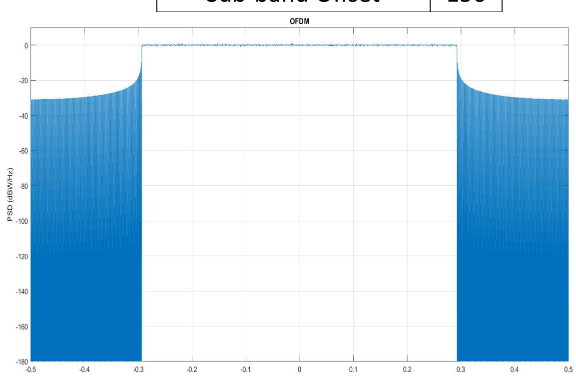

Fig. 7. The power spectral density of the OFDM transmit signal, 200 subcarriers

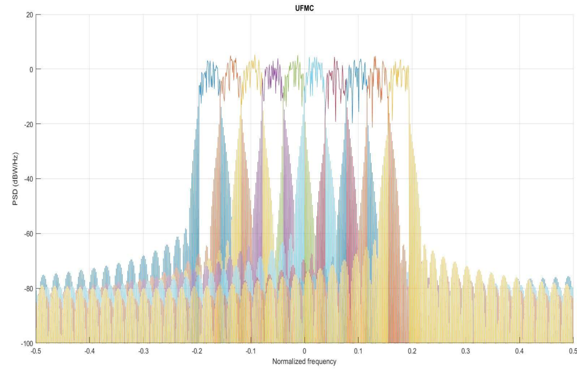

Fig. 8. The power spectral density of the UFMC transmit signal, 10 sub-bands 20 sub-carriers each

The PAPR for UFMC is 8.454 dB and for OFDM is 7.733 dB. The Power Spectral Densities (PSD) shown in figures 7 and 8 indicate lower side-lobes for UFMC allowing better utilization of the spectrum enhancing the spectral efficiency. The required SNR is calculated by adding noise to the received signal. The figure 9 and 10 show the constellation diagram of the symbols in UFMC. The BER is 0 and the SNR calculated is 16dB.

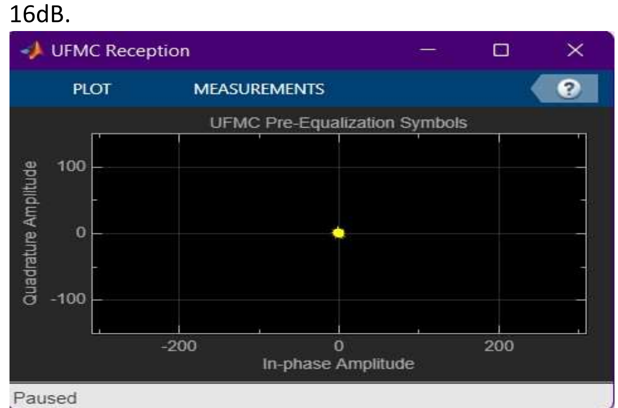

Fig. 9. Constellation diagram of symbols in UFMC

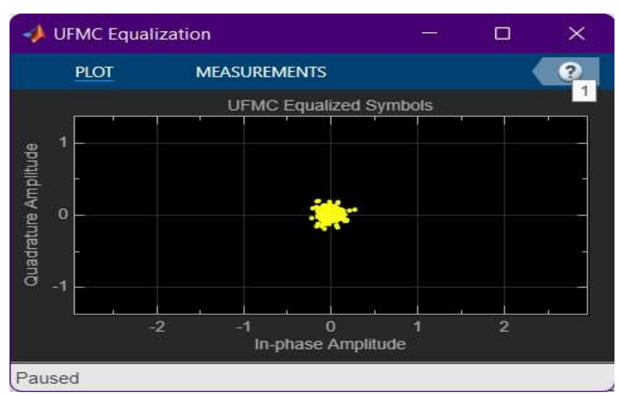

Fig. 10. Constellation diagram of symbols in UFMC

VI. CONCLUSION

The review of 5G modulation schemes was presented in this paper. In terms of Power Spectral Density, UFMC, FBMC, and F-OFDM multicarrier modulation schemes were compared to classic OFDM.

We also concluded that the BER performance of OFDM, FMBC and UFMC is almost same in Doubly-selective channels. Hence FBMC is a significant advance over OFDM; but it is still not feasible as there are many difficulties that arise when applying practical system aspects.So, UFMC acts as an improved version which includes the merits of FBMC. UFMC, due to its reduced trailing length, is better for signal transmissions that require low latency when compared to FBMC and is also able to provide complex orthogonality. UFMC has more spectral efficiency compared to OFDM. Hence, UFMC is a better candidate for 5G as compared to OFDM and FBMC.

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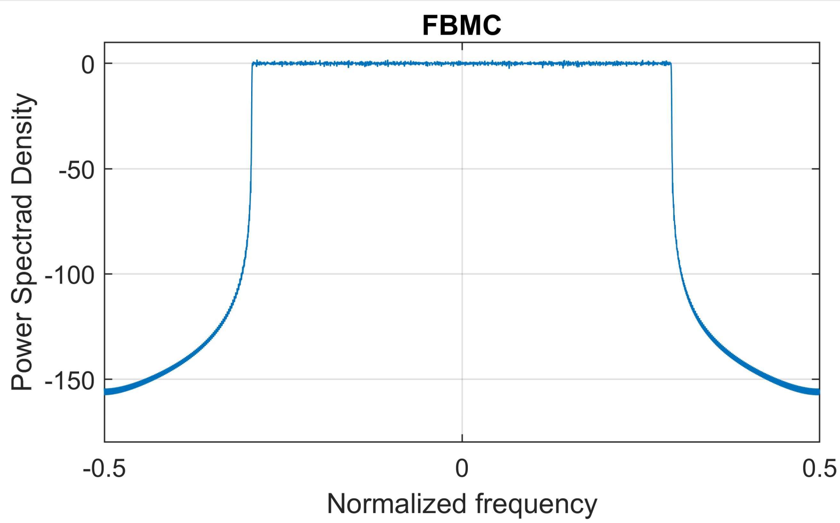
MATLAB CODE:

Comparison of FBMC and OFDM

```
% setting System Parameters
numFFT = 1024;
numGuards = 212;          K
= 3;
numSymbols = 100;
bitsPerSubCarrier = 2;
snrdB = 16;
```

```
switch K
case 2
        HkOneSided = sqrt(2)/2;
    case 3
        HkOneSided = [0.911438 0.411438];
case 4
        HkOneSided = [0.971960 sqrt(2)/2 0.235147];
otherwise         return end Hk =
[fliplr(HkOneSided) 1 HkOneSided];

L = numFFT-2*numGuards;
KF = K*numFFT;
KL = K*L;
dataSubCar = zeros(L, 1);
dataSubCarUp = zeros(KL, 1);

sumFBMCSpec = zeros(KF*2, 1);
sumOFDMSpec = zeros(numFFT*2, 1);

numBits = bitsPerSubCarrier*L/2;    inpData
= zeros(numBits, numSymbols); rxBits =
zeros(numBits, numSymbols); txSigAll =
complex(zeros(KF, numSymbols)); symBuf =
complex(zeros(2*KF, 1));

for symIdx = 1:numSymbols
    inpData(:, symIdx) = randi([0 1], numBits, 1);     modData =
qammod(inpData(:, symIdx), 2^bitsPerSubCarrier, ...
'InputType', 'Bit', 'UnitAveragePower', true);        if
rem(symIdx,2)==1
        dataSubCar(1:2:L) = real(modData);
dataSubCar(2:2:L) = 1i*imag(modData);     else
        dataSubCar(1:2:L) = 1i*imag(modData);
dataSubCar(2:2:L) = real(modData);     end
    dataSubCarUp(1:K:end) = dataSubCar;
    dataBitsUpPad = [zeros(numGuards*K,1); dataSubCarUp; zeros(numGuards*K,1)];
    X1 = filter(Hk, 1, dataBitsUpPad);
    X = [X1(K:end); zeros(K-1,1)];
```

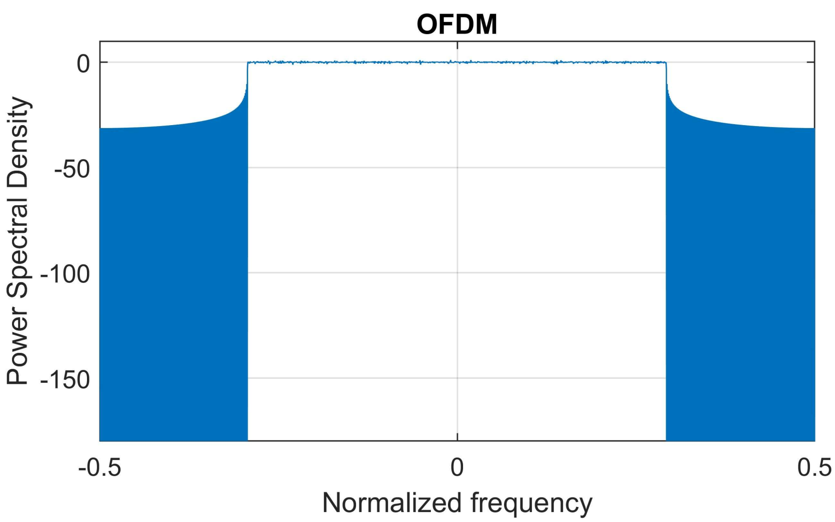
```
    txSymb = fftshift(ifft(X));
    symBuf = [symBuf(numFFT/2+1:end); complex(zeros(numFFT/2,1))];
    symBuf(KF+(1:KF)) = symBuf(KF+(1:KF)) + txSymb;

    currSym = complex(symBuf(1:KF));
    [specFBMC, fFBMC] = periodogram(currSym, hann(KF, 'periodic'), KF*2, 1);
sumFBMCSpec = sumFBMCSpec + specFBMC;

    txSigAll(:,symIdx) = currSym;
end

% Plot of power spectral density
sumFBMCSpec = sumFBMCSpec/mean(sumFBMCSpec(1+K+2*numGuards*K:end-2*numGuards*K-K));
plot(fFBMC-0.5,10*log10(sumFBMCSpec));
grid on
axis([-0.5 0.5 -180 10]);
xlabel('Normalized frequency');
ylabel('Power Spectrad Density')
title(['FBMC'])
set(gcf, 'Position', figposition([15 50 30 30]));
```



```
for symIdx = 1:numSymbols
    inpData2 = randi([0 1], bitsPerSubCarrier*L, 1);     modData =
qammod(inpData2, 2^bitsPerSubCarrier,'InputType', 'Bit', ...
        'UnitAveragePower', true);
    symOFDM = [zeros(numGuards,1); modData; zeros(numGuards,1)];
ifftOut = sqrt(numFFT).*ifft(ifftshift(symOFDM));
    [specOFDM,fOFDM] = periodogram(ifftOut, rectwin(length(ifftOut)), numFFT*2, 1,
    sumOFDMSpec = sumOFDMSpec + specOFDM;
end

sumOFDMSpec = sumOFDMSpec/mean(sumOFDMSpec(1+2*numGuards:end-2*numGuards));
figure;
plot(fOFDM,10*log10(sumOFDMSpec));
grid on
axis([-0.5 0.5 -180 10]);
xlabel('Normalized frequency');
```

```
'centered'
)
```

```
ylabel('Power Spectral Density')
title(['OFDM'])
set(gcf, 'Position', figposition([46 50 30 30]));
```



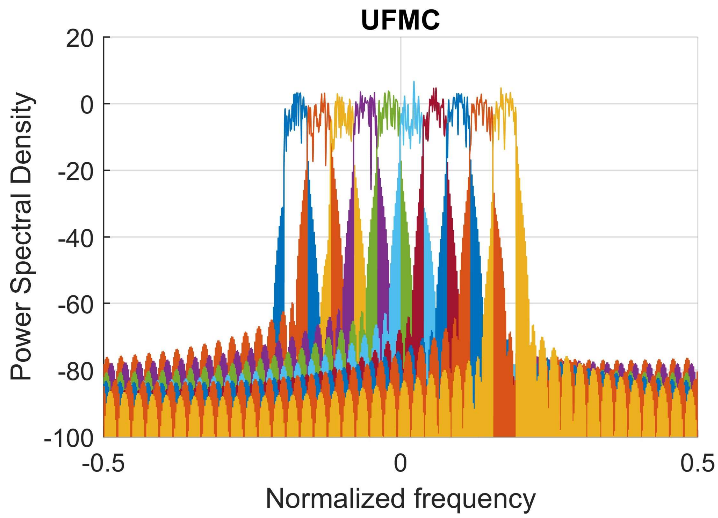
```
BER = comm.ErrorRate;

for symIdx = 1:numSymbols
rxSig = txSigAll(:, symIdx);
    rxNsig = awgn(rxSig, snrdB,
'measured');     rxf =
fft(fftshift(rxNsig));     rxfmf =
filter(Hk, 1, rxf);     rxfmf =
[rxfmf(K:end); zeros(K-1,1)];
    rxfmfg = rxfmf(numGuards*K+1:end-numGuards*K);
if rem(symIdx, 2)
        r1 = real(rxfmfg(1:2*K:end));
r2 = imag(rxfmfg(K+1:2*K:end));
rcomb = complex(r1, r2);     else
        r1 = imag(rxfmfg(1:2*K:end));
r2 = real(rxfmfg(K+1:2*K:end));
rcomb = complex(r2, r1);     end
    rcomb = (1/K)*rcomb;        rxBits(:, symIdx) = qamdemod(rcomb,
2^bitsPerSubCarrier, 'OutputType', ...
        'bit', 'UnitAveragePower', true);
end

BER.ReceiveDelay = bitsPerSubCarrier*KL;
ber = BER(inpData(:), rxBits(:));

disp(['FBMC Reception for K = ' num2str(K) ', BER = ' num2str(ber(1)) ...
     'at SNR =' num2str(snrdB) 'dB'])
```

```
FBMC Reception for K = 3, BER = 0at SNR =16dB
```

Comparison of FBMC and OFDM

```
% setting System Parameters
numFFT = 512;
subbandSize = 20;
numSubbands = 10;
subbandOffset = 156;
filterLen = 43;
slobeAtten = 40;

bitsPerSubCarrier = 4;  snrdB
= 16;
```

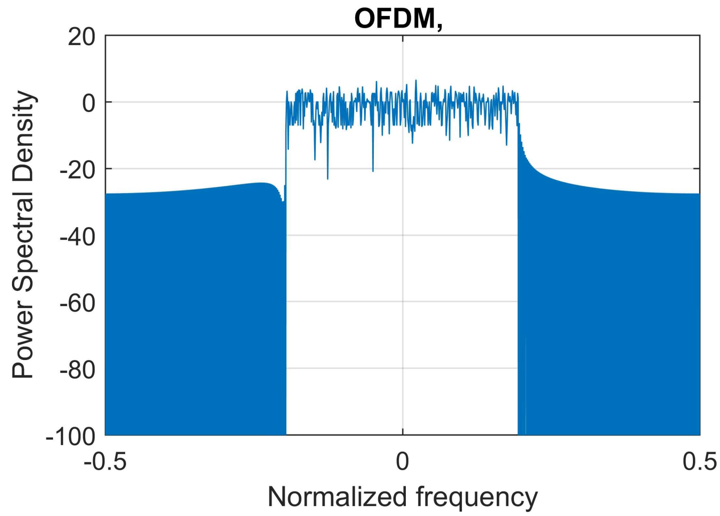
```
prototypeFilter = chebwin(filterLen, slobeAtten);
inpData = zeros(bitsPerSubCarrier*subbandSize, numSubbands);
txSig = complex(zeros(numFFT+filterLen-1, 1));

hFig = figure;
axis([-0.5 0.5 -100 20]);
hold on; grid on

xlabel('Normalized frequency');
ylabel('Power Spectral Density')
title(['UFMC'])

for bandIdx = 1:numSubbands
    bitsIn = randi([0 1], bitsPerSubCarrier*subbandSize, 1);     symbolsIn
= qammod(bitsIn, 2^bitsPerSubCarrier, 'InputType', 'bit', ...
        'UnitAveragePower', true);
inpData(:,bandIdx) = bitsIn;
    offset = subbandOffset+(bandIdx-1)*subbandSize;
    symbolsInOFDM = [zeros(offset,1); symbolsIn; zeros(numFFT-offset-subbandSize, 1)];
    ifftOut = ifft(ifftshift(symbolsInOFDM));     bandFilter = prototypeFilter.*exp(
1i*2*pi*(0:filterLen-1)'/numFFT*((bandIdx-1/2)* ...
        subbandSize+0.5+subbandOffset+numFFT/2) );
    filterOut = conv(bandFilter,ifftOut);
    [psd,f] = periodogram(filterOut, rectwin(length(filterOut)),numFFT*2, 1,
'centered');     plot(f,10*log10(psd));     txSig = txSig + filterOut;
end
set(hFig, 'Position', figposition([20 50 25 30]));
hold off;
```




```
PAPR = comm.CCDF('PAPROutputPort', true, 'PowerUnits', 'dBW');
[~,~,paprUFMC] = PAPR(txSig); disp(['PAPR for UFMC = ' num2str(paprUFMC)
' dB']);
```

```
PAPR for UFMC = 8.4367 dB
```

```
symbolsIn = qammod(inpData(:), 2^bitsPerSubCarrier, 'InputType', 'bit', ...
    'UnitAveragePower', true);

offset = subbandOffset;
symbolsInOFDM = [zeros(offset, 1); symbolsIn;zeros(numFFT-offset-subbandSize*numSubbands,
ifftOut = sqrt(numFFT).*ifft(ifftshift(symbolsInOFDM));

[psd,f] = periodogram(ifftOut, rectwin(length(ifftOut)), numFFT*2, 1, ...
    'centered'); hFig1
= figure;
plot(f,10*log10(psd));
grid on
axis([-0.5 0.5 -100 20]);
xlabel('Normalized frequency');
ylabel('Power Spectral Density')
title(['OFDM, '])
set(hFig1, 'Position', figposition([46 50 25 30]));
```

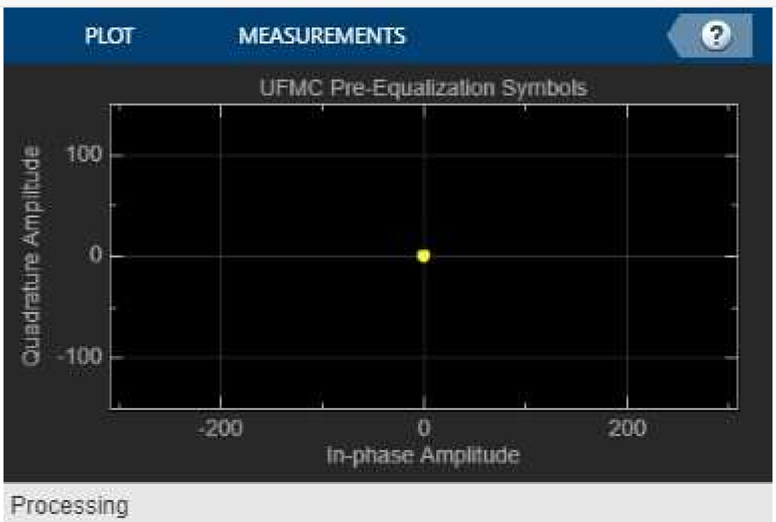



```
PAPR2 = comm.CCDF('PAPROutputPort', true, 'PowerUnits', 'dBW');
[~,~,paprOFDM] = PAPR2(ifftOut); disp(['PAPR for OFDM = '
num2str(paprOFDM) ' dB']);
```

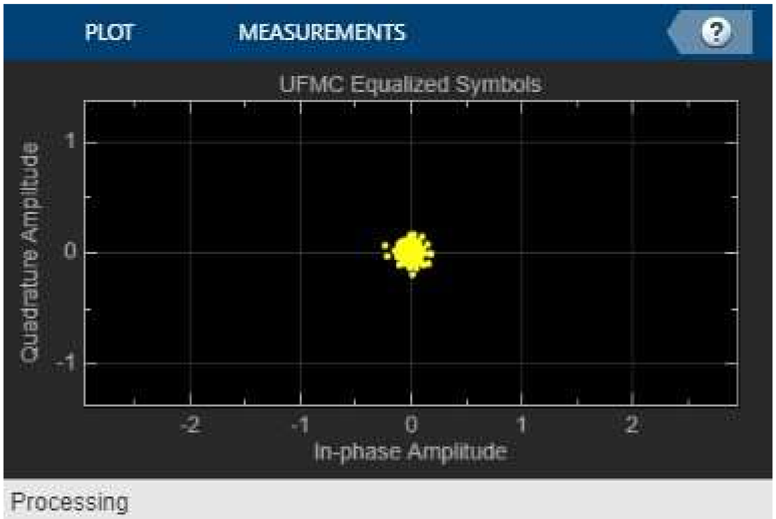
```
PAPR for OFDM = 7.7848 dB
```

```
rRxPadded = [rxSig; zeros(2*numFFT-numel(txSig),1)];

RxSymbols2x = fftshift(fft(rRxPadded));
RxSymbols = RxSymbols2x(1:2:end); dataRxSymbols =

RxSymbols(subbandOffset+(1:numSubbands*subbandSize));

constDiagRx = comm.ConstellationDiagram('ShowReferenceConstellation', false, ...
    'Position', figposition([20 15 25 30]), 'Title', 'UFMC Pre-Equalization Symbols',
...
    'Name', 'UFMC Reception', 'XLimits', [-150 150], 'YLimits', [-150 150]);
constDiagRx(dataRxSymbols);
```

```
rxf = [prototypeFilter.*exp(1i*2*pi*0.5*(0:filterLen-1)'/numFFT); zeros(numFFT-filterLen,1   )
prototypeFilterFreq = fftshift(fft(rxf));
prototypeFilterInv = 1./prototypeFilterFreq(numFFT/2-subbandSize/2+(1:subbandSize));

dataRxSymbolsMat = reshape(dataRxSymbols,subbandSize,numSubbands);
EqualizedRxSymbolsMat = bsxfun(@times,dataRxSymbolsMat,prototypeFilterInv);
EqualizedRxSymbols = EqualizedRxSymbolsMat(:);

constDiagEq = comm.ConstellationDiagram('ShowReferenceConstellation', false, 'Position',
    figposition([46 15 25 30]), 'Title', 'UFMC Equalized Symbols', 'Name',
constDiagEq(EqualizedRxSymbols);
```




```
...
'UFMC Equalization'
```




```
BER = comm.ErrorRate; rxBits = qamdemod(EqualizedRxSymbols, 2^bitsPerSubCarrier,
'OutputType', 'bit', ...
    'UnitAveragePower', true); ber = BER(inpData(:), rxBits); disp(['UFMC
Reception, BER = ' num2str(ber(1)) ' at SNR = ' num2str(snrdB) ' dB']);
```

```
UFMC Reception, BER = 0.515 at SNR = 16 dB
```

Key Paper:

A Review on 5G Modulation Schemes and Their Comparisons for Future Wireless Communications

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***Abstract*— The broadband data consumption has increased at a rapid rate to cope with the state of the art technology and features in the form of mobile phones which are smart and can execute various functions. The system capacity on the whole has to be increased to accommodate the latest wireless applications. This enhancement can be done by accessing new spectrum with increased data rates. With the ever increasing demand for frequency spectrum and resource availability limitation, Spectrum Pooling has gained immense popularity. The statistics show that most of the spectrum which is licensed is not utilized all the time. Spectrum Pooling or Sharing is the idea of using these spectrum holes or white spaces. In Dynamic Spectrum Access a secondary or a Cognitive user is capable of transmitting over distributed frequencies, while not interfering with the primary user. This leads to Multicarrier communication transmitting data across the channel in various frequency subcarriers at a reduced data rate. Filter Bank Multi-Carrier, Universal Filtered MultiCarrier, Generalized Frequency Division Multiplexing and Filtered Orthogonal Frequency Division Multiplexing are the potential competent new waveforms for 5G communication systems. This paper presents a review of the most capable waveform contenders for the 5G air interface. The parameters like efficiency in spectrum utilization, complexity and robustness of these waveforms are compared to OFDM which is being used in 4G.**

Keywords—5G Interface; multicarrier; spectral efficiency; subband filter

I. INTRODUCTION

The 4G cellular network and Long Term Evolution (LTE), were introduced recently. They provide high data bandwidth and are compatible with devices like smart phones and tablets [1]. The future 5G applications would be high speed high resolution streaming video, devices with artificial intelligence, network availability everywhere and every time, high speed gaming, revolution in production, automation, healthcare and energy. The greatest challenge is to support innumerable devices demanding fast entry to the network for transmitting trivial data. Also the traffic from low end sensors is latencysensitive and requires an ultra-resilient communication link. Extreme data rates for the users and subtle latency to the machines is to be supported. Fourth generation communications relies on Orthogonal Frequency Division Multiplexing (OFDM) [2]. OFDM is adopted in single frequency networks like Digital Video Broadcast (DVB), Digital Audio Broadcast (DAB) and in indoor wireless systems, such as IEEE 802.11 and Hiperlan2 [3]. OFDM is a special case of transmission with many carriers. It divides the spectrum into subcarriers and separates them by introducing guard bands. These carriers overlap but are orthogonal due to the nature of the pulse shaping. The Inter-Symbol Interference (ISI) can be removed by using a Cyclic Prefix. One-tap equalizer can be used at the receiver side. OFDM has numerous advantages like protection against interference, resistant to fading, simpler channel equalization and it is computationally efficient. However the superior side lobes and the stringent timing requirements make the bandwidth efficiency a failure. The important necessities enabled by the fifth generation (5G) modulation scheme are potential usage of signals with excessive data rate, afford minimal delay for lengthy and concise data, prompt exchange of data in the uplink and downlink, option of cost effective broadcasting by reducing the on time of the devices working with small data rates. The 5G modulation schemes are Filter Bank Multi-Carrier (FBMC), Universal Filtered Multi-Carrier (UFMC), Generalized Frequency Division Multiplexing (GFDM), Filtered OFDM (fOFDM).

II. MODULATION SCHEMES

A. OFDM-Orthogonal Frequency Division Multiplexing

In multiple carrier transmission method the available channel bandwidth is subdivided into several parallel sub-channels that are called subcarriers. Multiplexing in frequency and time domain is possible. The spacing Δf between these subcarriers is selected such that they are non frequency selective and experience a flat gain in the frequency domain. For OFDM, several subcarriers are spaced at $\Delta = 1/$[illegible] , referred to as orthogonality. The transmitter and receiver block diagram implementation is shown in figure 1.

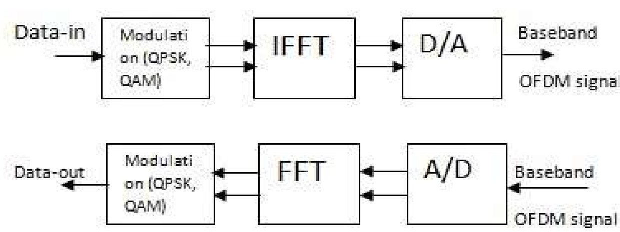

Fig. 1: OFDM Transmitter and Receiver

B. FBMC- Filter Bank Multi-carrier

FBMC does not use cyclic prefix and filters each sub-carrier individually. Spectrum efficiency is prominent in this scheme. The tapered filters used for the subcarriers need stretched time constants. This is almost four times the length of the symbol in the primary multiple carrier. This will result in overlapping of the symbols in time. Orthogonality is accomplished by using offset-QAM modulation scheme. Hence in complex plane FBMC vectors are not perpendicular to each other [4]. It provides means to permeate the restrictions of low spectrum efficiency and precise synchronization necessities of OFDM [7].

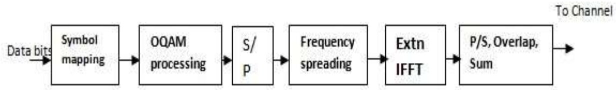

Fig. 2: a) FBMC Transmitter

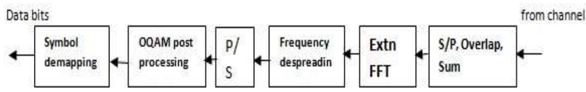

Fig. 2: b) FBMC Receiver

Each subcarrier in the modulated signal is filtered. The filters are described by the factor K. It represents the multiple carrier symbols that overlap in the time. Usage of tapered filters for the sub-carriers in FBMC facilitates the use of more number of digital filter taps compared to the entire sub-carriers. The IFFT length is fixed same as the total sub-carrier number and time domain processing method is suitable. As per the scheme developed by PHYDYAS the model filter preferred is *2*(K-1)* where *K* = 2, 3, or 4 [8]. When a PHYDAS filter is selected as the FBMC filter, orthogonality between the Offset-QAM (OQAM) sub-carriers is fully assured. OQAM is achieved by shifting the in-phase components of a QAM system by half of the symbol length T/2 versus the out-phase components. If the time-shift is applied to the in-phase part of a carrier, it is applied to the out-phase part of its neighbors, interference is reduced to every second carrier. The OQAM receiver cancels out the Inter Carrier Interference (ICI) by simply not considering the fraction of the received character without data. The use of OQAM eliminates the need for guard times and cyclic prefix that is therefore optional in FBMC [8] and thus increases spectral efficiency. The processing in the receiver block is done using Matched filter. The data is recovered after the demodulation of OQAM. Figure 2(a) and (b) depict the FBMC block diagram. The merits of this modulation scheme are transmitting in asynchronous mode, appropriate for cognitive radio, strong enough to adjust to extreme mobility and adjustment of the time duration within one band efficiently. However, the issues to be solved are scattered pilot becomes more complex, MIMO schemes do not work easily, carrier guard between users needed in uplink, inefficient for short bursts due to long filter tails [12].

C. UFMC- Universal Filtered Multi-Carrier Modulation

UFMC is the enhanced version of Cyclic Prefix-OFDM. The signal is divided into numerous sub-bands before filtering instead of filtering each subcarrier independently [5]. Cyclic prefix is not used. It may be used to enhance protection against ISI. The filtering of the signal is done using Dolph-Chebyshev filter of length L. The symbol duration is N+L-1 [9]. The orthogonality between the subcarrirs is maintained and the use of OQAM modulation can be avoided. The N subcarriers are divided into subbands. All subbands have fixed number of subcarriers and may not be used for transmission. Computation of N-point IFFT is done by zero padding for the unallocated carrier. The sub-band responses are summed. The receiver uses FFT of length 2N. The N even bins contain the symbol information and the N odd bins have ICI [12]. UFMC transmitter and receiver are shown in Figure 3 (a) and (b).

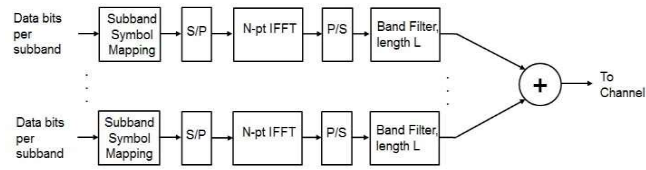

Fig. 3: a) UFMC Transmitter

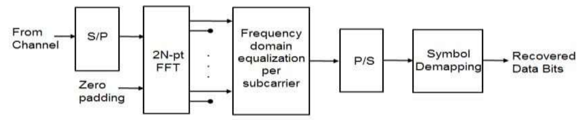

Fig. 3: b) UFMC Receiver

The advantages of UFMC are good spectral efficiency, less overhead required, suited for short burst transmissions and enabling low latency modes. However, the challenges are UFMC is not suited for high data rates, more delay spread and requirement of multi-tap equalizers.

D. GFDM-Generalized Frequency Division Multiplexing

GFDM is an adaptable multiple carrier transmission method. Unlike the other schemes the carrier Orthogonality is not maintained. The out-of-band emissions can be managed in a better way and Peak to Average Power Ratio (PAPR) can be lowered [6]. The filtering of each subcarrier is done individually. The available spectrum for each user is spread into multiple spectral segments. This concept makes it suitable to implement cognitive radio. CP is added to each character. The Root raised Cosine filter using circular filtering called tail biting is used [10]. The data is in the form of blocks and each block preceded with CP is divided into several sub-symbols. This leads to flexibility of using short number of sub-symbols for applications involving latency and all the sub-symbols can be used for one specific user in applications where time is the constraint. Adjacent sub-carriers overlap resulting in nonorthogonal waveform. However, asynchronous data transmission is possible. This results in high BER with a need for equalization and methods to remove the interference at the receiver. The transceiver diagram is shown in Figure (4). The advantages of GFDM are low PAPR, out-of-band emission reduction by filter adjustment, multiuser scheduling in time and frequency domain, spectrum hole clustering, efficient equalization and transmission which is block based [10]. The disadvantages are complex receiver, use of matched filter for removing interference and OQAM makes MIMO difficult [12, 13].

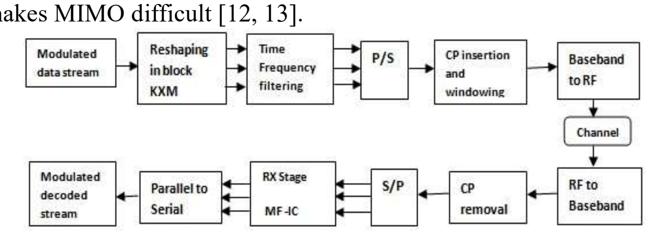

Fig. 4: GFDM transceiver

E. F-OFDM: Filtered Orthogonal Frequency Division Multiplexing

As the name indicates, filtering is the distinctive feature of *f*OFDM. The existing bandwidth is divided into number of subbands. Distinct services are provided in the sub-bands depending on the application. The spectrum is utilized in a much better way by accommodating a range of services. It is the extension of the classic OFDM with an additional subband filter and flexibility in changing the parameters like length of cyclic prefix, transmission time interval and subcarrier spacing.

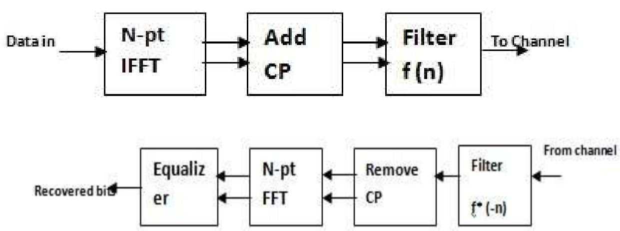

Fig. 5: a) f-OFDM Transmitter b) f-OFDM Receiver

The sub-band filter employed is a short equiripple filter which enhances the out-of-band emission of the sub-band signal. The duration of the filter may go beyond the CP duration. The inter-symbol interference can be removed with windowing technique. Flexibility in parameterization allows the usage of different sub-bands to different users. For high latency applications, the duration of the symbol can be reduced and sub-carrier spacing can be increased. The sub-band filter removes the inter sub-band interference [11]. Implementation of the receiver is the opposite of the transmitter blocks. The same model filter is used. The transmitter and receiver blocks implementation is shown in fig 5(a) and (b). The advantages of Filtered OFDM are flexibility in parameterization according to the application, good out of band rejection of leakage, supporting asynchronous transmission and co-existence of the waveform. The disadvantages of Filtered OFDM are implementation and structure complexity [13].

III. COMPARISION OF UFMC, FBMC AND F-OFDM WITH OFDM

The UFMC, FBMC and F-OFDM are compared with the generic OFDM modulation scheme. The merits of these 5G modulation schemes are highlighted. Though each one has its demerits, still the candidate 5G schemes show considerable improvement compared to OFDM.

A. UFMC Vs OFDM

The simulation parameters for UFMC are shown in Table I. The OFDM uses the fully occupied band without cyclic prefix.

Table I: Simulation parameters for UFMC

FFT size	512
Sub-band size	20
Number of sub-bands	10
Filter length	43
Side lobe attenuation	40 dB

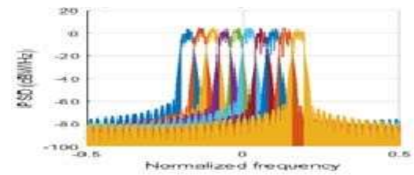

Fig. 6: a) Power Spectral Density of UFMC

The PAPR for UFMC is 8.2379 dB and for OFDM is 8.8843 dB. The Power Spectral Densities (PSD) shown in figures 6(a) and (b) indicate lower side-lobes for UFMC allowing better utilization of the spectrum enhancing the spectral efficiency. With the reduced crest factor (PAPR) in UFMC, more bits can be transmitted with low power hardware. The UFMC receiver is modeled with no channel effects. The required SNR is calculated by adding noise to the received signal. The figure 7(a) and (b) show the constellation diagram of the symbols in UFMC. The BER is zero and the SNR calculated is 15dB.

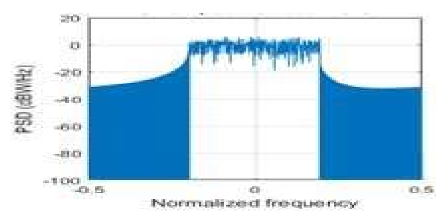

Fig.6: b) Power Spectral Density of OFDM

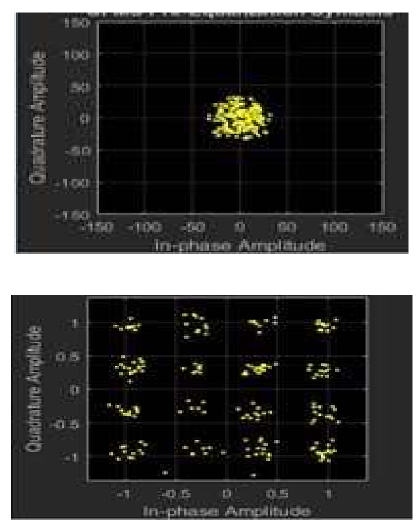

Fig. 7: Constellation diagram of symbols in UFMC

B. FBMC Vs OFDM

The simulation parameters for FBMC are shown in Table II.

Table II: Simulation parameters for FBMC

FFT size	1024
Number of guard bands	212
Spreading factor, overlapping factor (k)	4
Number of symbols	100
Bits per subcarrier (4QAM)	2
SNR	12 dB

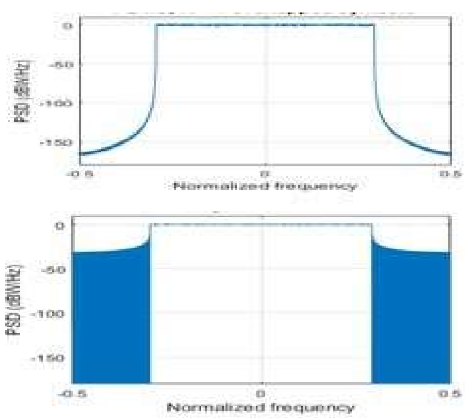

Fig.8: a) PSD of FBMC b) PSD of OFDM The plot of the Power Spectral Densities shown in figures 8(a) and (b) indicate lower side-lobes for FBMC allowing better utilization of the spectrum enhancing the spectral efficiency. The receiver demodulator is implemented and the BER is measured in the absence of the fading channel. BER is determined after filtering and OQAM separation of the data symbols. The BER for the FBMC receiver with overlapping factor of 4 is zero for 12 dB SNR.

C. F-OFDM Vs OFDM

The simulation parameters for F-OFDM are shown in Table III.

Table III: Simulation parameters for F-OFDM

FFT size	1024
Number of RBs	50
Number of sub-carriers/RB	12
CP length	72
Bits per subcarrier (64QAM)	6
SNR	18 dB
Filter length	513

The Sinc impulse response filter with flat pass-band and sufficient attenuation in stop band is constructed using window. The impulse response is shown in Figure 9. The PAPR for F-OFDM and OFDM are 11.371 dB and 9.721 dB respectively. The plot of the Power Spectral Densities shown in figures 10(a) and (b) indicate lower side-lobes for F-OFDM allowing better utilization of the spectrum enhancing the spectral efficiency. Matched Filter is used in the receiver block. Processing of the received signal is done using this filter. The fading channel is not used and the noise is added to the signal received and the desired SNR is achieved. The BER is 0.00083333 at 18 dB SNR. Figure (11) shows the constellation diagram of the demodulated symbols.

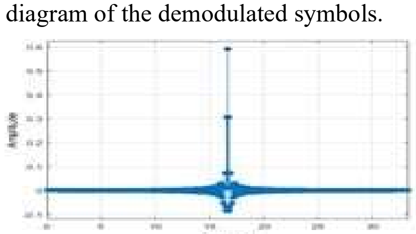

Fig. 9: Impulse response of filter

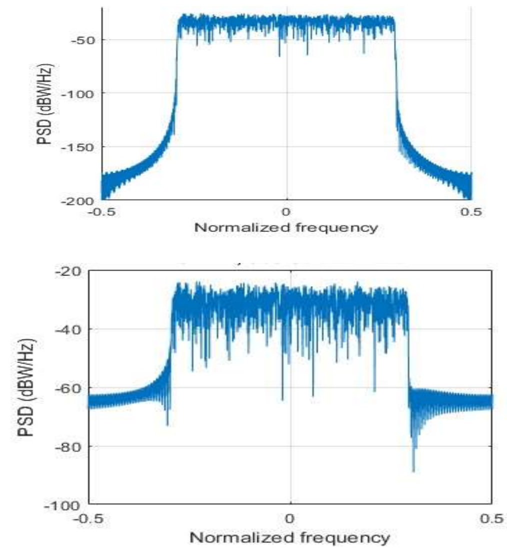

Fig. 10: a) PSD of F-OFDM b) PSD of OFDM

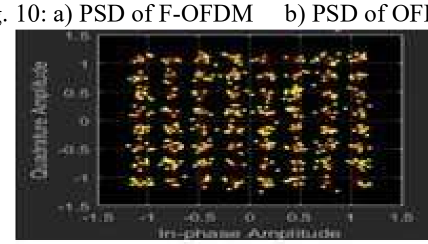

Fig. 11: Constellation diagram of symbols in F-OFDM

IV. CONCLUSIONS

In this paper the review of the candidate 5G modulation schemes was presented. The comparisons of UFMC, FBMC and F-OFDM multicarrier modulation schemes were done with the classic OFDM in terms of Power Spectral Density. The three schemes are showing better spectrum efficiency when compared to OFDM. For UFMC and F-OFDM the crest factor was also calculated and UFMC showed reduction in PAPR. All the receivers were analyzed without introducing the fading channels and the SNR was calculated. The BER for UFMC and FBMC was zero. Compared to UFMC, FBMC incurs more filter delay due to the per subcarrier filtering and also requires OQAM processing. Hence for MIMO applications modifications are necessary.

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