SPECTRAL SHAPING FOR BLOCK MODULATION

A Project Report

submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **SPECTRAL SHAPING FOR BLOCK MODULATION**, submitted by **SARATH B**, to the Indian Institute of Technology, Madras, for the award of the degree of **DUAL DEGREE**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: 5G ; OFDM; WOLA-OFDM; AW-OFDM

5G is the latest iteration of cellular communications technology envisioned to provide and improve on existing standards on the parameters of coverage, data rate, latency, and reliability. It is understood that OFDM due to its poor frequency localisation/out of band radiation and spectral shape, won't match the requirements of 5G multi carrier waveform.

AW OFDM was conceptualised as a multi carrier waveform to improve on the various parameters of OOB radiations/frequency localisation, Peak to Average Power ratio, Bit error rate; with least complexity in design and lenient requirement of timing synchronization over the other Multi-carrier waveform candidates for 5G. The simulation results for comparison between OFDM, WOLA (Weighted Overlap Add) and AW-OFDM confirmed the advantage of the new waveform in terms of Adjacent Channel Interference (ACI), Bit error rate (BER) performance and window flexibility,

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ABBREVIATIONS

OFDM	Orthogonal Frequency Division Multiplexing
WOLA	Weighted Overlap and Add
AW-OFDM	Asymmetric Windowed Orthogonal Frequency Division Multiplexing
BER	Bit Error Rate
PAPR	Peak to Average Power Ratio
5G	5th Generation
4G	4th Generation
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
IFFT	Inverse Fast Fourier Transform
FFT	Fast Fourier Transform
IDFT	Inverse Discrete Fourier Transform
DFT	Discrete Fourier Transform
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
AWGN	Additive White Gaussian Noise
FBMC	Filter Bank based multi-carrier
UFMC	Universally filtered multi-carrier
SNR	Signal to Noise Ratio
CCDF	Complementary Cumulative distribution function
ACI	Adjacent Carrier Interference

NOTATION

N	FFT size
Nt	Windowing Taper Region Length
Ncp	Cyclic Prefix length
h	fading coefficient
D	Diagonalised channel
I_N	Identity Matrix of size N
ω	Angular Frequency

CHAPTER 1

INTRODUCTION

5G is the upcoming version of Wireless communication which comes with increased standards of mass connectivity, ultra-wide band, low latency etc. The 5G wave forms are expected to have Very high spectral efficiency to meet its criterion's, However it is understood that OFDM which is used for the 4G technology is incapable of meeting the requirement that 5G demands because of it poor frequency localisation/out of band Emission.

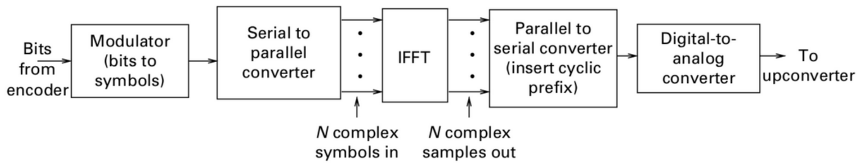
This research work proposes a new waveform called AW-OFDM. AW-OFDM is conceptualised as a modified version of OFDM that improve on the various parameters of Out Of Band radiations/frequency localisation, Peak to Average Power ratio, Bit error rate; with least complexity in design and lenient requirement of timing synchronization over the other Multi-carrier waveform candidates for 5G. Simulations were performed comparing different aspects of OFDM, WOLA-OFDM & AW-OFDM and the results confirms the same.

1.1 Introduction to OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a digital multicarrier modulation scheme that extends the concept of single subcarrier modulation by using multiple subcarriers within the same single channel. Rather than transmit a high-rate stream of data with a single subcarrier, OFDM makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel. Each subcarrier is modulated with a conventional digital modulation scheme (such as QPSK, 16-QAM, etc.). However, the combination of many subcarriers enables datarates similar to conventional single-carrier modulation schemes within equivalent bandwidths.

1.2 OFDM Transceiver Chain

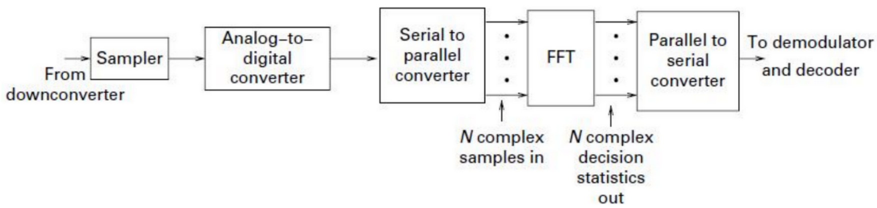
OFDM uses an inverse Fast fourier Transform as modulator. Bits are converted to symbols and these symbols are modulated with an IFFT and then added with cyclic prefix as shown in the figure below.



Suppose **X** is the symbol set to be transmitted
Actual Transmitted samples will be Inverse fast Fourier transform of the symbols

$$\mathbf{x} = IFFT(\mathbf{X}) = F^{*}\mathbf{X}$$

where F is the unitary FFT matrix. Cyclic prefix is added to **x** before transmission to make the data unaffected from the Inter-block interference introduced by the channel. These samples are passed through the ADC and transmitted through the channel.
The received signals are processed as the following:



The received symbols at the output of the Analog to digital converter are of the form.

$$\mathbf{Y} = \mathrm{H}\mathbf{x} + \mathbf{W}$$

This form is formed by converting the linear convolution to circular convolution. H is the channel Matrix, Channel matrix looks the following:

$$H = \begin{bmatrix} h[0] & 0 & \dots & h[2] & h[1] \\ h[1] & h[0] & \dots & h[3] & h[2] \\ \vdots & \vdots & \ddots & 0 & \vdots \\ 0 & 0 & \dots & \ddots & \ddots \end{bmatrix}$$

This matrix is a circulant matrix which means it has the following property.

FH = DF

H = F*DF

D=Diagonal Matrix= $FFT(1^{st})$ column of H,F is the unitary DFT matrix and IDFT matrix $F^* = F^{-1}$

FFT of the received samples are taken at the receiver, then the symbols are decoded.

$$\mathbf{y} = H\mathbf{x} + N = F^*DFF^*\mathbf{x} + N$$

FFT is applied at the receiver

$$\mathbf{Y} = W\mathbf{Y} = WW^*DW.W^*\mathbf{x} + WN = D\mathbf{x} + N'$$

$D = I_N$ if it is an AWGN channel.
Decoding is done to get the estimate of transmitted bits.

1.3 Limitations of OFDM

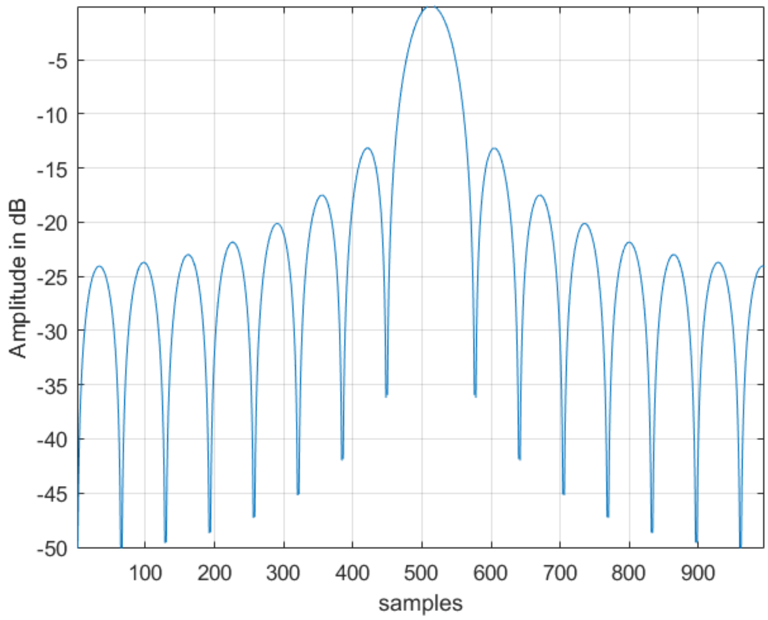
The data symbols in OFDM are transmitted using Inverse fast Fourier transform.

$$\mathbf{x} = F^*\mathbf{X}$$

The magnitude response of each of the sub-carriers is actually a digital sic pulse in the frequency domain. Frequency response of a Digital Sinc filter is as shown below.

$$H(\omega) = \frac{Sin(\frac{\omega N}{2})}{Sin(\frac{\omega}{2})}$$

which look like the following:



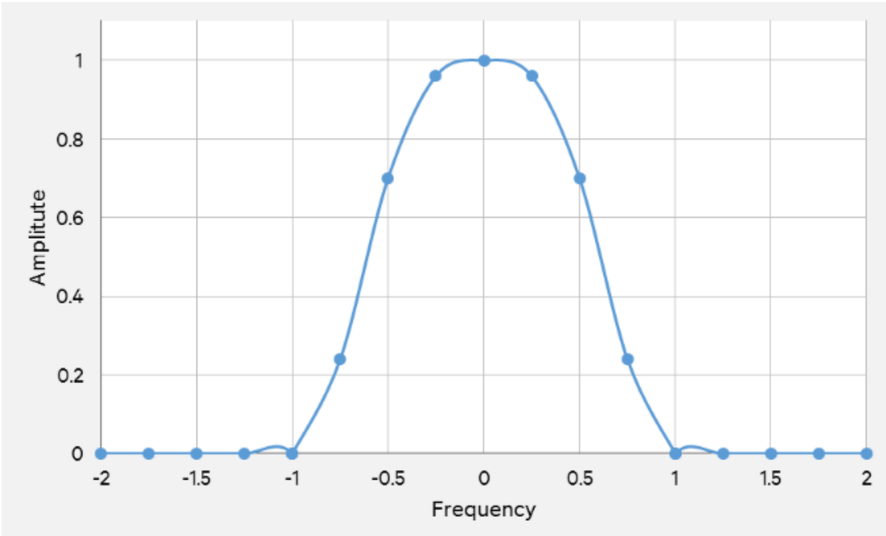
It is very clear from the response of the digital sinc that its response reduces down very slowly, the second sidelobe is 13dB slow than than the main lobe. This property of the digital sinc causes huge out of band leakage for OFDM in the frequency domain..

1.3.1 Schemes for Out of Band Reduction

Out of band emissions in the OFDM is due to the Digital Sinc Roll off and due to the rectangular windowing used in the OFDM. Reduction of out of band can be achieved through many methods like FBMC, UFMC etc.

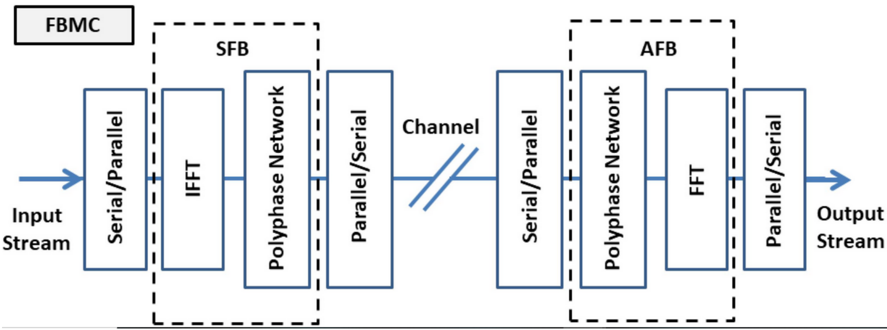
FBMC

FBMC is Filter Bank based multi-carrier modulation. Filter bank multicarrier is an evolved version of OFDM FBMC is a form of multicarrier modulation in which the carriers are filtered to provide a more spectral efficient form of waveform. FBMC uses a different Filter other than using the traditional Digital Sinc filter, Frequency response of the FBMC looks like the following:



[1]

The whole transmitter receiver chain looks like the following:



[2]

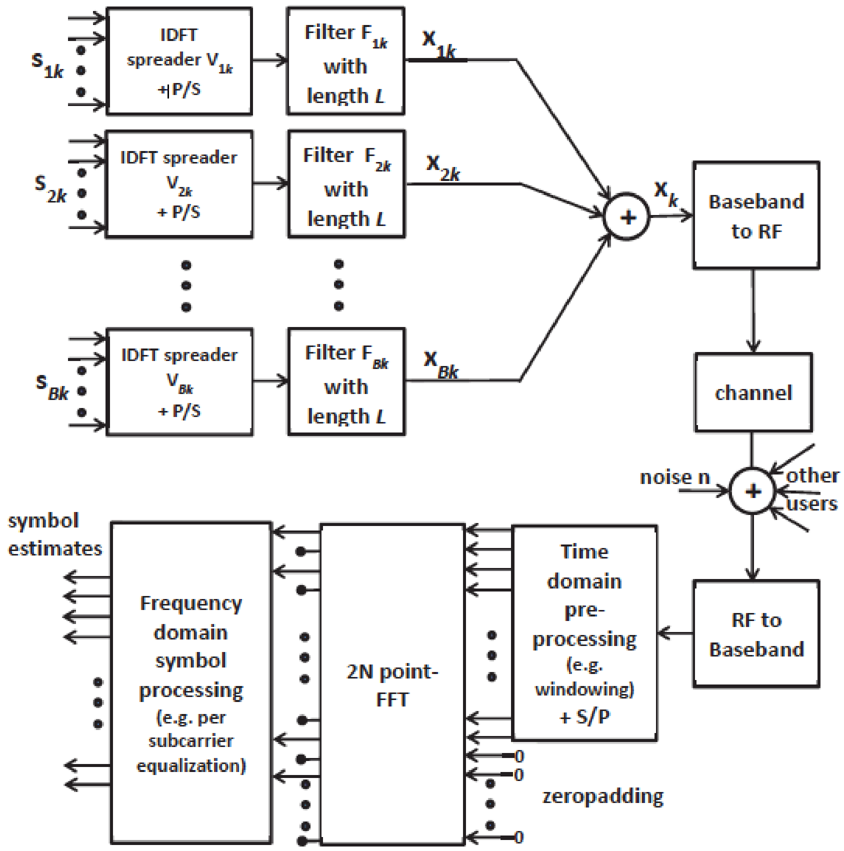
From the above mentioned figure it shows that the transmitter and the receiver use polyphase Network which is a filterbank introduced to reduce the sidelobe leakage. When carriers were modulated in an OFDM system, sidelobes spread out either side. With a filter bank system, the filters are used to remove these and therefore a much cleaner carrier results.

UFMC

UFMC stands for Universally filtered multi-carrier Modulation, UFMC applies filtering to subsets of the complete band instead of single subcarriers or the complete band. This scheme filters a set of sub-carriers in the frequency domain using chebyshev's filter to reduce down the out of band leakage.

[1]Qualcomm Technologies Inc. 5G Waveform Multiple Access Techniques November 4, 2015
[2]Spectral Efficiency Analysis in Massive MIMO using FBMC-OQAM Modulation Felipe Kurpiel Jose1,Luis Henrique Lolis2,Samuel Baraldi Mafra3,Eduardo Parente Ribeiro4

The whole transmitter receiver chain looks like the following:



[3]

In the above figure UFMC use B number of filters during the transmission to reduce the Power leakage. UFMC provides lower sidelobe leakage compared to OFDM but higher leakage compared to FBMC.

1.3.2 Drawbacks of FBMC and UFMC

FBMC is more complicated than OFDM - it introduces an overhead in overlapping symbols in the filter bank in the time domain. The use of MIMO with FBMC is very complicated and as a result few systems have investigated the use of these two techniques together.The design of wide bandwidth and high dynamic range systems with FBMC provides some significant RF development challenges.

UFMC cannot support Cyclic prefix hence it can incur from multi-path fading, UFMC has both transmitter complexity and receiver complexity because of using 2x size FFT compared to OFDM.

[3]A Survey on Candidate Waveforms for 5G: Which One Has the Edge?,Oguz Kislal

Both of these methods needs complex processing at the transmitter and receiver in terms of memory, filters, poly phase Networks etc. Therefore In this thesis we have looked at low complexity schemes like WOLA-OFDM(Weighted Overlap and add OFDM).

CHAPTER 2

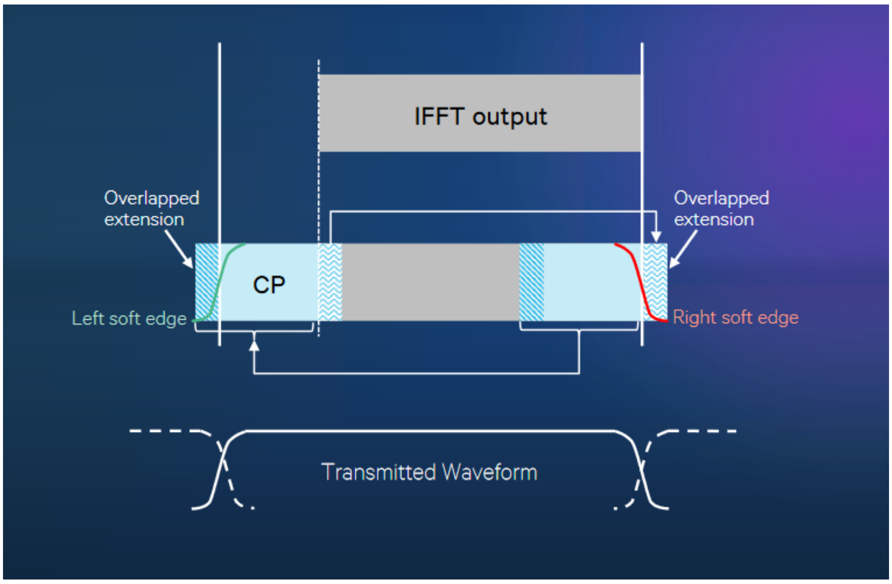
Weighted Overlap and Add OFDM - (WOLA-OFDM)

WOLA OFDM Stands for Weighted overlap and Add OFDM. WOLA-OFDM is a modified version of OFDM. WOLA brings gives out of band leakage but at the same time lesser complexity than the schemes like FBMC, UFMC etc.In WOLA-OFDM the conventional usage of rectangular pulse shape is avoided. But, a pulse with soft edges is used instead. Weighted Overlap and Add as the name indicates the processing includes a weighting operation, overlapping and addition. These are explained in details in the next section.

2.1 WOLA-OFDM processing

WOLA OFDM uses a transmitter and receiver processing, but the processing complexity if WOLA OFDM is considerably lesser than FBMC, UFMC etc, but it is more complex compared to OFDM processing.

2.1.1 Transmitter processing of WOLA OFDM



[1]

[1]Qualcomm Technologies Inc. 5G Waveform Multiple Access Techniques November 4, 2015

Initial processing of WOLA OFDM is same as the OFDM processing. Suppose **X** is the symbol set to be transmitted
Actual Transmitted samples will be Inverse fast Fourier transform of the symbols

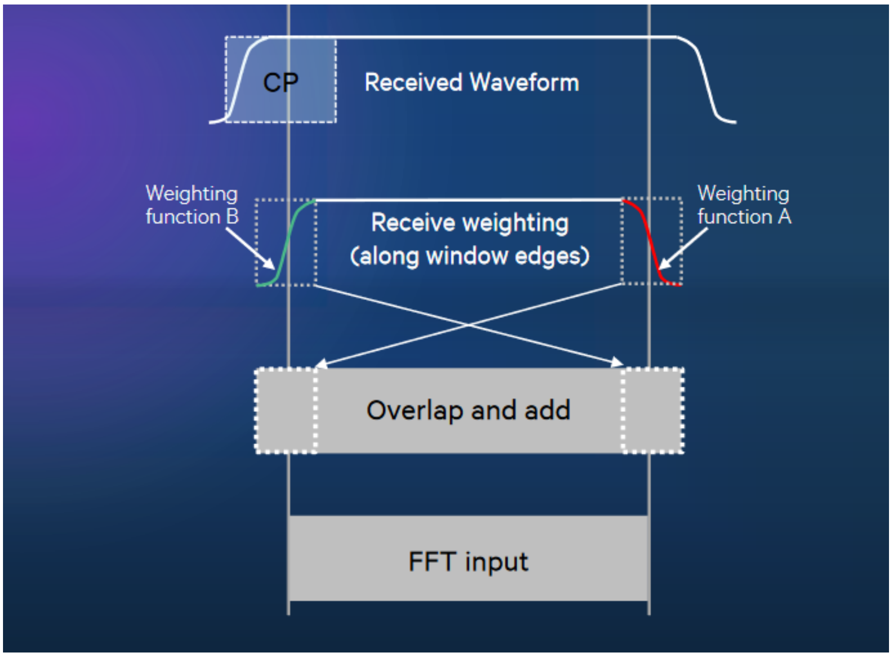
$$\mathbf{x} = IFFT(\mathbf{X}) = F^{*}\mathbf{X}$$

After the IFFT stage cyclic prefix is added to the samples and then an extended cyclic prefix is added for Nt samples and an extend cyclic post-fix is given for Nt samples making the total number of samples $N + Ncp + 2Nt$. A windowing is performed for $2Nt$ sampling at both the ends. The windowing is usually a Raised cosine taper region or Square root raised cosine window. N : size of FFT
Ncp : number of cyclic prefix
The window looks like the following for the first $2Nt$ samples.

$$w[n] = 0.5\left(1 - \cos\frac{2\pi n}{2Nt-1}\right) 1 \leq n \leq 2Nt$$

The rightmost side of the block is multiplied with the mirror image of the same window for $2Nt$ samples.
Overlapping operation is performed consuming $2Nt$ samples from each end of the block with the previous and future blocks which makes the effective length of the new block to be $N + Ncp$. The length of the OFDM block is also $N + Ncp$. Overlapping step ensures that there is no extra overhead/loss of specral efficiency compared to OFDM and windowing step gives a low out of band leakage.

2.1.2 Receiver processing of WOLA OFDM



[2]

At the receiver $N + Ncp$ samples are received per block, due to the operations of windowing and overlapping Nt samples from each end of the block gets corrupted and effectively $2Nt$ portion out of each block is affected by the window and overlap, hence it cannot be used for decoding. Decoding is performed by picking the samples which are not affected by the window, in other words this is a critical windowing operation or Number of flexible windowing at the receiver is 1. Once these set of samples are captured at the receiver again a weight overlap and add operation is done as shown in the figure with the same window taper region as used in the transmitter. N samples are chosen out of the useful samples and passed to the input of the FFT stage.This stage the received samples are of the form.

$$\mathbf{Y} = \mathrm{H}\mathbf{x} + \mathbf{W}$$

Processing done after the Weight overlap and add is same as that of OFDM.

2.2 Limitations of WOLA OFDM

WOLA OFDM has a few disadvantages despite of having lower out of band leakage. The limitations of WOLA OFDM are the following:

[2]Qualcomm Technologies Inc. 5G Waveform Multiple Access Techniques November 4, 2015

2.2.1 Windowing Flexibility

Flexibility of windowing is a benefit in receiver processing because the notion of time which the user and the Base-station have is different and a timing slip will happen if the synchronisation is not done very frequently which leads to picking up set of N samples with Inter Block interference. Therefore having a flexibility in windowing reduces the requirement of frequent synchronization.

In the WOLA Receiver processing there is a stage where unwindowed portion of the received block is captured exactly without any flexibility, This operation allows only a critical windowing or flexibility of 1.

2.2.2 Receiver complexity

WOLA OFDM need more complex receiver processing compared to OFDM because of the weight overlap and add stage at the receiver processing.

2.2.3 Increased PAPR

Peak to average Power ration is defined as:

$$\mathrm{PAPR} = \frac{\max\left\{|s(nT_s)|^2\right\}}{E\{|s(nT_s)|^2\}}, n \in [0, N + Ncp - 1]$$

Peak to Average power ratio is higher for WOLA OFDM compared to OFDM. This is because Interblock interference is introduced in the transmitter itself.

CHAPTER 3

Asymmetric Windowed OFDM - (AW-OFDM)

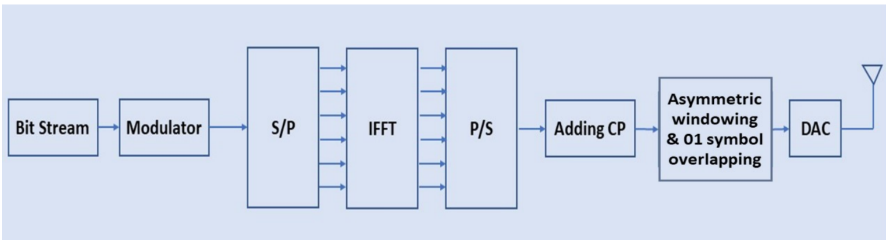
Asymmetric Windowed OFDM or AW-OFDM is a method that this thesis proposes. AW-OFDM is conceptualised as a modified version of OFDM but the transmitter and receiver complexity is very less compared to other modified versions of OFDM. This method provides 5 advantages compared WOLA-OFDM.

3.1 AW-OFDM Tranceiver chain

AW-OFDM is a windowing based technique but less complex compared to WOLA-OFDM.

3.1.1 AW-OFDM Transmitter

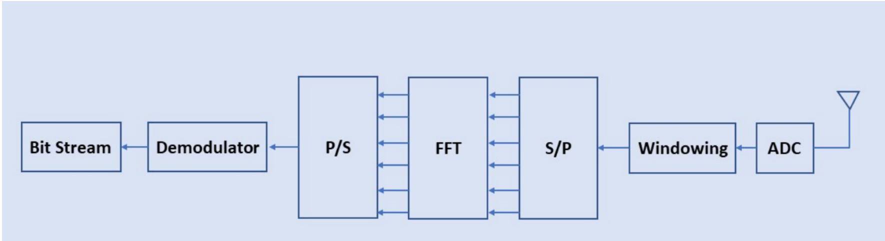
Transmitter processing of AW-OFDM is same as the OFDM except we add a windowing operation and a sample overlap.



Symbols are modulated using IFFT and added with Cyclic prefix. After the cyclic prefix is added and an asymmetric window operation is done with a sample overlap. This is transmitted through the channel. The transmitted samples are $N + Ncp$ samples per block, hence have the same overhead/spectral efficiency as OFDM.

3.1.2 AW-OFDM Receiver

AW-OFDM Receiver picks $N + Ncp$ samples per block.



N samples are windowed from $N + Ncp$ received samples, these set of N samples are passed through the FFT stage. The receiver processing in AW-OFDM is very similar to that of OFDM.

3.1.3 Advantages of AW-OFDM

AW-OFDM due to its transmitter processing provides lots of advantages over WOLA-OFDM. The following are the advanges of AW-OFDM over WOLA -OFDM

1) Lower Out of Band Leakage

2) Low complexity receiver Processing

3) Increased Flexibility of windowing

4) Lower BER at given SNR

5) Lower PAPR compared to WOLA, but comparable PAPR with OFDM

3.2 Performance Comparions

Simulation of WOLA-OFDM, OFDM and AW-OFDM was done with the following parameters.

Simulation parameters

Bandwidth	10MHz	**FFT size**	1024
Sampling Frequency	15.36MHz	**CP length**	108
Modulation	QPSK	**Occupied Subcarriers**	601
Taper Region *Nt*	16	**Guard**	423
Subcarrier Spacing	15kHz	**Occupied BW**	9.015Mhz
D	3Nt	**Roll off factor(RC)**	1

3.2.1 Windowing flexibility

Windowing flexibility is actually the sets of N samples that can be chosen out of $N + Ncp$ which are actually free from Inter block interference.

Lets assume the delay spread is D and T_S is the sampling time, then we get the following results for 3 schemes.

OFDM

OFDM has a windowing flexibility of $Ncp - D$, these many samples will be free from Inter block interference. we can choose any set of consecutive N samples and pass it to the input of the FFT stage.

WOLA-OFDM

WOLA-OFDM has a receiver processing which requires a critical windowing step hence the Windowing flexibility of WOLA OFDM is actually 1 with the receiver processing.
If the WOLA OFDM is processed without the receiver processing we will get only a felxibility of $Ncp - D - 2Nt$. Because the WOLA OFDM is transmitted with windowing $2Nt$ samples at the transmitter itself.

AW-OFDM

In the case of AW-Windowing, only there is a loss of Nt samples at the end due to the windowing and the Asymmetric window will be consumed by the Inter-block-Interference.

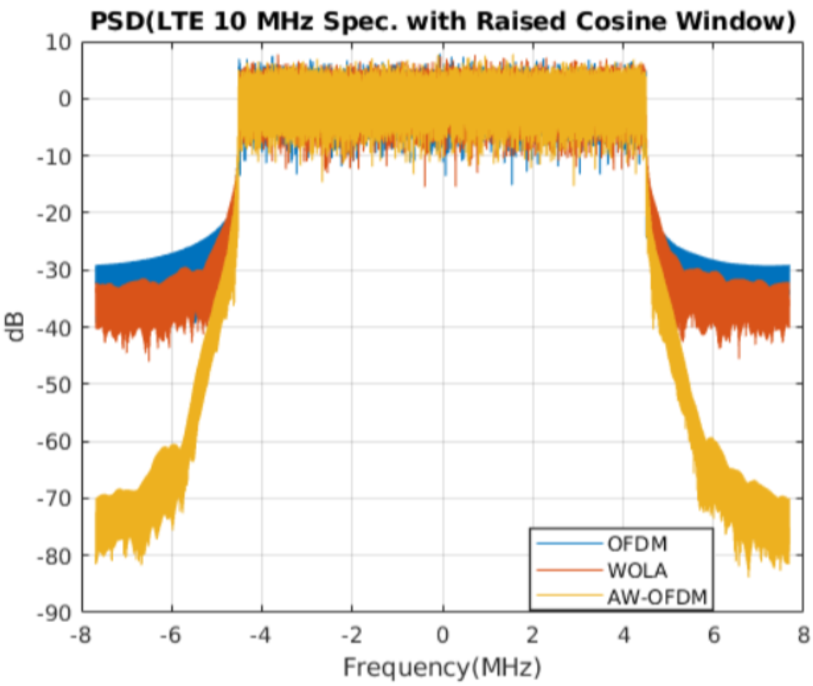
Hence the windowing flexibility of the AW-OFDM will be $Ncp - D - Nt$. Hence we have more flexibility than WOLA-OFDM.

3.2.2 Receiver Complexity

The AW-OFDM has a very similar receiver processing like OFDM where we pick N samples out of $N + Ncp$ samples, whereas the WOLA-OFDM has a complicated receiver processing which includes a windowing , overlapping and addition.

3.2.3 Power Spectal Density

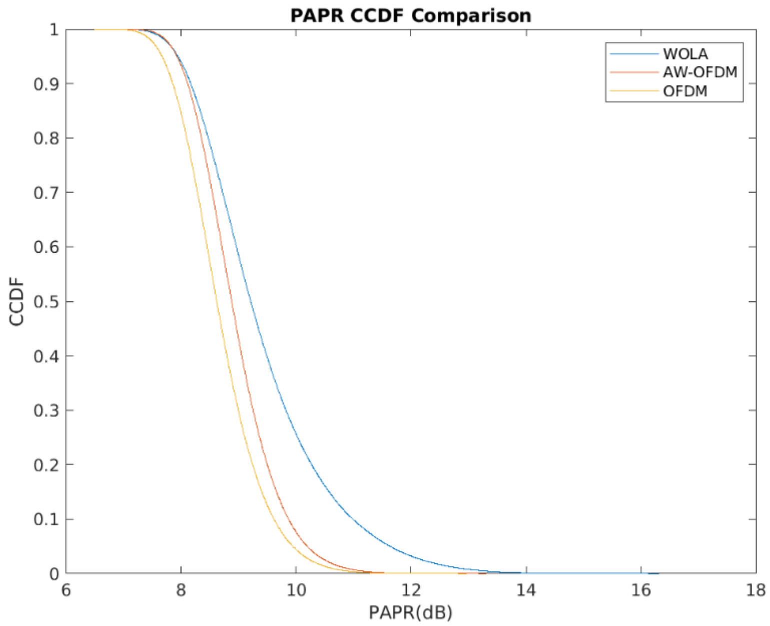
Power spectral density is defined as the FFT of auto-correlation. Power spectral density shows the Out of Band leakage for a particular waveform.Simulations were performed comparing the performances of OFDM, WOLA-OFDM and AW- OFDM which provided the following Result:



This show that AW-OFDM has a very high side-lobe suppression compared to OFDM and WOLA-OFDM, which is a great advantage for any waveform because the guard bands needed for the side-lobe suppression becomes very less. Hence AW-OFDM can transmit more data in a given band compared to OFDM and WOLA OFDM, in other words this waveform provides high spectal Efficiency.

3.2.4 PAPR

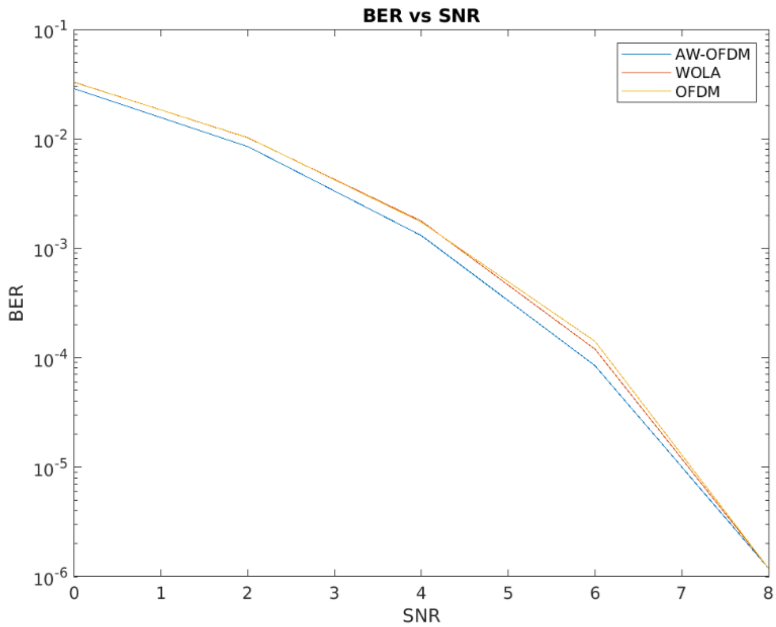
Peak to average power ratio comparison done with OFDM and WOLA OFDM.



Increaded PAPR at the transmitter leads to saturation in the Power amplifier stage, which leads to loss of orthogonality at the subcarrier levels. This result shows that the PAPR of AW-OFDM is smaller compared to WOLA-OFDM and its comparable with that of OFDM.

3.2.5 BER comparsion

Comparison of Bit Error Rate was done with OFDM and WOLA-OFDM. This Bit Error rate was computed by keeping the same transmitted power for 3 wave-forms.



The results show that the AW-OFDM has has more coding gain than other schemes.

CHAPTER 4

CONCLUSION

Flexible and efficient use of the available spectrum targeting heterogeneous mobile network deployment scenarios is one of the key challenges that future 5G systems would need to tackle. To maximize the spectrum efficiency,5G air interface technologies will need to be flexible, efficient and require least complexity for deployment. Classic OFDM has been intensively studied in the past. In this thesis, a fair comparison of past waveforms and a new potential waveform candidate has been made under the framework of PAPR, BER, Windowing flexibility and ACI.

The new potential waveform AW-OFDM was found to be better than the other prospective waveform WOLA. The waveform due to its significantly low ACI has good characteristics for asynchronous multi-user uplink scenarios. With slight increase in complexity the new waveform provides significant advantages over classic OFDM and WOLA as confirmed from the simulations.

REFERENCES

1)5G Waveform Multiple Access Techniques-Qualcomm Technologies, Inc.

2)WOLA-OFDM: a potential candidate for asynchronous 5 G R. Zayani et.al

3)Spectral Efficiency Analysis in Massive MIMO using FBMC-OQAM Modulation Felipe Kurpiel Jose1 et.al