

# Inquiry and Enactment of Ultra-Wideband Receiver in Multi- Band OFDM System

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**Abstract:** Traditional OFDM based transmission system uses Cyclic Prefix (CP) in an OFDM symbol in order to maintain orthogonality of transmission. Present days' Ultra-Wideband (UWB) systems use Multi-Band OFDM (MB-OFDM) techniques for transmission in application like Wireless Personal Area Network (WPAN). UWB based systems are power limited by the regulation of FCC. CP introduces correlation in the transmitted data sequence and hence introduces ripples in the power spectral density (PSD) of the transmitted data. This in turn reduces the range of data transmission. However, use of zero-pad suffix (ZPS) will have a flat PSD and hence does not suffer from the range degradation problem. In the receiver, ZP removal requires use of a technique called as overlap and add (OLA) in order to capture the multipath energy of the channel and maintain the orthogonality in the received data. During transmission, the length of the ZP is fixed and equal to the channel length. During reception, in traditional OFDM receiver, the OLA is done using a ZP length of same as channel length as transmitted. In UWB receiver the FFT window gets smeared due to multipath fading and hence estimation of true FFT window start point does affect the OLA process and hence the overall system performance. In this paper, we propose a method which adapts OLA length in UWB receiver depending on the current band of reception and the band wise estimated true FFT window start point. The proposed method is more beneficiary for high delay spread channel like channel model 4 (CM4). In CM4, the technique can achieve around 1 dB  $E_b/N_0$  gain at  $10^{-2}$  of BER, while simulated over uncoded MB-OFDM based UWB system.

**Keywords:** Cyclic prefix, ZPS, UWB, OFDM, WPAN, OLA, FCC, FFT, Channel Mode, ADC, DAC

## 1. Introduction

Since its humble beginning in the decade of 1940, ultra wideband (UWB) technology has traveled a rich path, from lab to military, back to lab, and now ready to flourish in the overwhelming consumer electronics market space, particularly in wireless universal serial bus (WUSB) and wireless personal area network (WPAN) domain. The UWB technology brings in the benefit of high bit rate communication what broad spectrum can offer. The key lies in Shannon's channel capacity equation (1), which relates the channel capacity (C), with the channel bandwidth (W) and signal to noise ratio (S/N).

$$C = W \log_2 \left( 1 + \frac{S}{N} \right) \quad (1)$$

As C varies linearly with W, but logarithmically with S, so it is easier to increase bit rate, C, by increasing channel bandwidth, W, rather than increasing signal power, S. Although broad spectrum helps to increase the bit rate, it cannot increase the range of communication and hence power limited UWB systems are suitable for small-range high-speed communication. Over last few decades there has been some research interest on UWB system design. However the World has seen a real explosion on UWB research since Federal Communications Commission (FCC) allowed license free operation of a wide spectrum of 7.5 GHz (3.1 GHz to 10.6 GHz) in the year 2002. FCC ruled that UWB system must have instantaneous spectrum of more than 500 MHz or more than 20% of its central frequency. They also constrained the power spectral density not to exceed  $-41.3$  dBm/MHz, so that UWB systems appear in the thermal noise floor of the existing narrowband services like GSM, GPS etc., and coexist with them without affecting their performance [1-2]. Efficient utilization of such a large bandwidth of 7.5 GHz creates a huge challenge to the system designer community. Moreover the power constraints limits the range of communication to a short range only around 2 m to 15 m with scalable data rate of 53.3 Mbps to 480 Mbps and also create a serious coexistence problem of UWB in the existing narrowband transmission environment.

Traditional UWB systems use short time-domain pulses of the order of 500 ps to 2 ns to occupy the wide spectrum. The information is then transmitted by modulating these time-domain pulses either in time or in phase. Generation of this transmitted signal using analog circuitry is simple. But such an extreme wide spectrum makes the design of analog and mixed signal circuitry such as analog to digital converter (ADC), digital to analog converter (DAC) etc. and uphill task. Moreover high frequency makes power consumption to shoot up and hence makes this approach less attractive. Another challenge of this approach is it requires large number of fingers in RAKE receiver in order to capture sufficient energy in a dense multipath scenario making the baseband design quite

complex. As we have seen that wide spectrum poses several challenges to UWB system design, one approach would be to divide the whole wide spectrum in several sub-bands, each having bandwidth (BW) of greater than 500 MHz, as regulated by FCC, and then use the same time domain pulses to generate the UWB signal interleaved in different bands. This is often referred as pulsed multiband technique and overcomes serious problem associated with the very narrow time domain pulses by using relatively fat time-domain pulses on the order of 2 ns to 4 ns. Like the previous scheme here also pulse position modulation (PPM) or binary phase shift keying (BPSK) scheme is used to modulate the time-domain pulses according to the information to be transmitted. The main advantage of this scheme is that information is processed over a much smaller BW reducing the power consumption, cost, and system design complexity. This also improves the spectral flexibility which in turn helps UWB systems to follow global compliance. However the dwell time for a band is around 4 ns to 8 ns and this poses a serious problem of capturing sufficient amount of multipath energy and hence achieving the data rate promised by UWB spectrum, particularly in non-line -of-sight (NLOS) path environment having typical channel delay spread of around 40 ns to 70 ns which is much higher than dwell time. This can be solved if we use multiple RF chain, but again that will increase the complexity, cost and power consumption of the system. Many disadvantages associated with pulsed multiband technique can be overcome if we can use symbol which is much longer in time domain and incorporating a modulation technique that can efficiently capture multipath energy. Multiband-Orthogonal Frequency Division Multiplexing (MB-OFDM) is the right candidate for this choice [3]. In this approach information is transmitted using OFDM symbol and interleaved over multiple bands, so that power of transmission remains same as the transmission scheme using the whole band instantaneously. The OFDM reaps its own benefits to this approach [4, 5] in terms of spectral efficiency, narrow band interference (NBI) mitigation, excellent robustness against multipath channel, and facilitating the use of low complexity equalizer in receiver. MB-OFDM based UWB system takes all the positives offered by the multi -banding scheme i.e. low power, low cost, simple analog design etc., and also is capable of capturing sufficient multipath energy using a single RF chain due to OFDM scheme adopted. Among the several proposals by different standardization groups, MB-OFDM has been accepted as commercially more viable compared to impulse radio based or code division multiple access (CDMA) based UWB transmission. ECMA-368 is one of such leading standard employing MB-OFDM technique [6]. In MB-OFDM technique the whole spectrum of 3.1 GHz to 10.6 GHz is divided into 14 bands, each of BW of 528 MHz. All the 14 bands are grouped into 5 band-groups as shown in Fig. 1. Band-group #1 to #4 is having 3 bands each, whereas band-group #5 is having only 2 bands. At present band-group #1 is made compulsory for use, and the rest is kept for future expansions. Texas Instruments has

come up with time frequency interleaving (TFI) scheme by which the OFDM signal hops over three bands across time [3], [8]. Fig. 2 shows one example of TFI scheme employed in MB-OFDM system. OFDM symbol duration is 312.5 ns. Out of that, 60.6 ns is the cyclic prefix (CP) or zero pad (ZP) duration and 9.5 ns is guard interval, kept to ease switching between different bands.

This paper proposes an adaptive reception technique for ZP based systems in an attempt to minimize ISI incursions from subsequent OFDM symbols. In section II, we review the impact of CP and ZP in OFDM systems in general, and outline one of the key motivation factors for this paper. In section III, we relook the ZP removal process in view of multi-band UWB system. In section IV, we discuss our proposed adaptive overlap-add technique. Section V discusses our simulation results and finally we conclude our paper in section VI.

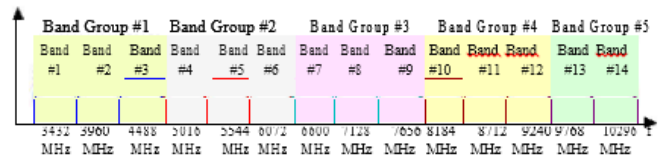


Fig. 1. Band planning for MB-OFDM system following ECMA-368 standard

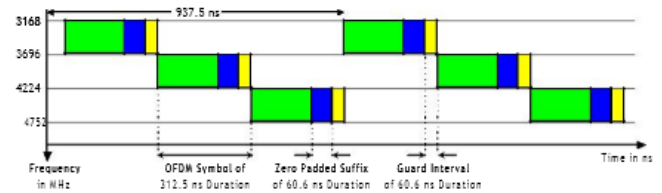


Fig. 2. Example of a time frequency coding for MB-OFDM system. Here the band hopping sequence is band # 1, 2, 3.

## 2. CP VS ZP in ofdm based system

In traditional OFDM systems, a cyclic prefix is used before the OFDM symbol in order to maintain the orthogonality in the received signal after passing through the multipath channel. However as CP introduces a structure in the symbols transmitted, the system suffers from the ripple in the power spectral density (PSD) necessitating power back-off in the transmitter which can be as large as 1.5 dB for MB-OFDM based system [9]. In an alternative, it was pointed out in [7], that we can use zero-padding instead of cyclic-prefix in the transmitted OFDM symbols. The transmission using ZP does not suffer from the ripple in PSD and hence can transmit at maximum power and hence to a longer distance. However to retain the circular convolution property, which essentially provides robustness against multipath channel for OFDM system and facilitates the use of a single-tap frequency domain equalizer in receiver, we require to do a slight modification in signal processing in OFDM receiver. CP based system, can simply discard the CP portion of the received symbol, and however for ZP based system we need to do overlap-add (OLA) operation in the receiver shown in Fig. 3.

In general, the ZP length should be greater than the delay

spread of the channel. As per ECMA-368, this length is 32 samples. Due to multipath propagation, the received OFDM symbol gets smeared at the most by 32 samples, as per assumption that channel length is not greater than 32 samples duration. To mimic what would have happened if there were CP in the transmitted symbol, we need to do overlap-add operation in the receiver. This is illustrated in Fig. 4. First we should estimate the start point of true FFT window. As the FFT length in ECMA-368 is 128 samples, from that we should count and pick up 32 consecutive received samples starting from 129th sample onwards. Then we should do a sample-by-sample addition as following. If  $r(n)$  is the received samples and  $n=0$  corresponds to the true FFT window start point, then overlap-add process modifies  $r(n)$  as per eqn. (2).

compared to CP based system. This is one of the key motivation factors of this paper.

### 3. ZP removal in view of multi-band timing synchronization (MBTS) algorithm

In UWB, we see four type of channel models proposed for research and developmental work, they are CM1, CM2, CM3 and CM4. Without going into details of them, it should be highlighted that CM1 corresponds to small delay spread channel, whereas delay spread increases as we go towards CM4 [11 and references therein]. In [9] and [10], it is pointed out that there exists an overlap-add length ('ZP\_LEN' in Fig. 4) for which the receiver performs optimally. This is because for small delay spread channel (say CM1 with a delay spread of 4 samples as one realization), if we use  $ZP\_LEN = 32$  samples, then we are essentially picking up some (28 in this example) pure noise samples during overlap-add process, which affects BER adversely. This essentially means we should estimate the channel delay spread and use a variable 'ZP\_LEN' during overlap-add procedure, as outlined in [9-10]. The estimation of channel delay spread can be done in a few ways mainly from the cross-correlation characteristics in time domain in timing synchronizer block and one of the methods has been proposed in [9]. This type of adaptive overlap-add method based on estimation of channel delay spread is more beneficiary for small delay spread channel and hardly benefits anything for large enough delay spread channel. It also should be pointed out that the above method demands a very small estimation error in locating the FFT window, which is quite difficult to achieve in UWB system. On the other hand, in [11], it was pointed out that the mean delay of the UWB channel differs significantly depending on the band of transmission. Accordingly they have proposed a timing synchronization algorithm, which they called as multi band timing synchronization (MBTS) algorithm, which essentially proposes to estimate the true start point of FFT window depending on the band of transmission. Note that, this variance of mean delay is due to the manifestation of the multipath channel in multi-band scenario while the channel length remains same. Hence it may happen for a band, the FFT start point might get estimated say at the sample number 16, rather than 0 or closed to 0. In that case if we use a fixed 'ZP\_LEN' of 32 samples for overlap-add operation, then we are essentially picking up samples from the next OFDM symbol which leads to ISI. Figure 5 shows the offset sensitivity of BER performance of MB-OFDM system. Here offset = 0 implies the true start point of FFT window if there is no noise and there exists a non-zero multipath component at the first sample location. Note that, even if there is no non-zero multipath component at 0th location, still a start point of FFT window at that location will always perform optimally in no noise condition, because equalizer can take care as no multipath component to equalizer will appear as non-causal component. Note that, the curves show that MB-OFDM system is quite sensitive to the ISI incursions from the next OFDM symbol.

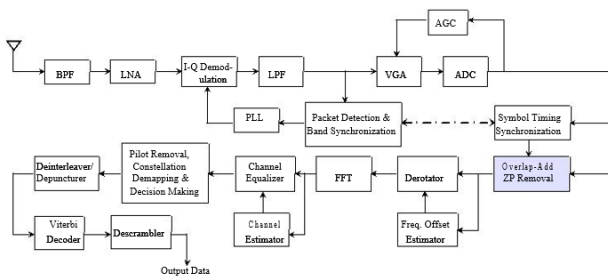


Fig. 3. A typical MB-OFDM based receiver architecture

$$r'(n) = r(n) + r(n + 128) \text{ for } n = 0 \text{ to } 31, \\ = r(n), \text{ otherwise.} \quad (2)$$

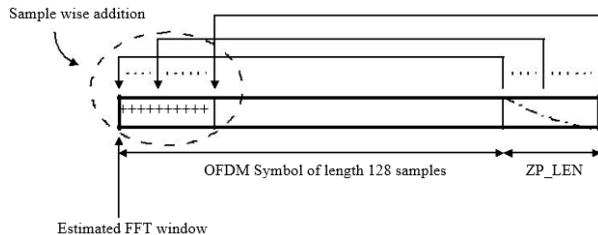


Fig. 4. OFDM Symbol of length 128 samples

Note that, CP based system is not very sensitive to symbol timing synchronization error. As long as we estimate the start of the FFT window in the portion of CP, the equalizer can correct the phase offset incurred due to the estimation error. However a ZP based system requires more accurate estimation of the start of FFT window. This is because in CP based system the circular convolution is an effect of natural phenomenon. The physical propagation of the OFDM signal through multipath channel causes linear convolution, which appears to be a circular convolution due to the cyclic property artificially maintained due to CP addition. However linear convolution does not appear naturally as circular convolution for ZP based system. Overlap-add operation makes sure this artificial circular convolution appearance, which depends on the true start point of the FFT window. Hence ZP based system is quite sensitive to the timing synchronization estimation error

#### 4. Proposed adaptive overlap-add technique

In this section we propose a technique to reduce the ISI incursions from the subsequent OFDM symbol due to the use of fixed ‘ZP\_LEN’ during overlap-add process. At the same time we try to make the method robust with respect to the estimation error of the true start point of the FFT window in the smeared received signal. In general the timing synchronizer block provides the estimated offsets over different bands as signed numbers because the estimation point can shift in left as well as right depending on the situation. If any of the estimated offsets becomes negative, we first make all of them positive using the following algorithm (Alg#1) and provide necessary delay in data path in order to make the receiver a causal system.

##### Alg#1:

Say,  $OB_i$  denotes the signed offset of band  $i$ , where  $i \in 1, 2, \text{ or } 3$ . Let  $UOB_i$  denotes the unsigned offset of band  $i$  after making the system causal.

If (  $OB_1 < 0$  or  $OB_2 < 0$  or  $OB_3 < 0$  ) Then

{

For  $i = 1$  to 3, % ‘ $i$ ’ is the band number

$UOB_i = OB_i + \max(\text{abs}(\text{all negative } OB_j))$ ;

Where  $j \in 1, 2, 3$ .

}

Else,

$UOB_i = OB_i$  ;

We notice that it is expected that  $(OB_i \sim OB_j) \leq 32$ ,  $i, j$  belonging to band number, as the channel length is 32 samples. This also guarantees that the range of  $UOB_i$  is 0 to 32. The variation in  $UOB_i$  is solely due to channel manifestation and the channel length remains same as 32 samples. So to avoid ISI incursion from the next OFDM symbol we use band-dependent variable ZP length (‘ZP\_LEN\_  $B_i$ ’) during overlap-add operation over multiple bands as per the following algorithm (Alg#2).

##### Alg#2:

For  $i = 1$  to 3, % band number

$ZP\_LEN\_B_i = 32 - \{UOB_i - \text{Min}(UOB_1, UOB_2, UOB_3)\}$  ; End for loop;

Note that in Alg#2, apart from making the scheme robust to the estimation error of the true start point of the FFT window, we have also made sure that the chances of the equalizer of seeing non-causal multipath components minimal. The above algorithm (Alg#2) is valid for single band or dual band transmission as well. For single band transmission, the process ceased to be band dependent adaptive and becomes fixed ‘ZP\_LEN’ as 32 samples. So, as per Alg#2, a band-dependent

‘ZP\_LEN’ number of samples after the FFT window is picked up and added to the front portion as shown in Fig. 4.

#### 5. Simulation results

Figure 6 shows the BER curves for uncoded MB-OFDM based UWB system with and without band wise variable ZP length for overlap and add operation. For large delay-spread channels in UWB systems the mean excess delay is more compared to small delay-spread channels. This implies for large delay spread channel, the estimation of FFT window will be more away from the true FFT window resulting in more ISI incursions from next OFDM symbol. Hence the proposed technique is more promising for large delay-spread channels. The curves show a significant amount of performance improvement (for CM4 around 1 dB of  $E_b/N_0$  savings at  $10^{-2}$  BER for uncoded system) is achieved for large delay-spread channels.

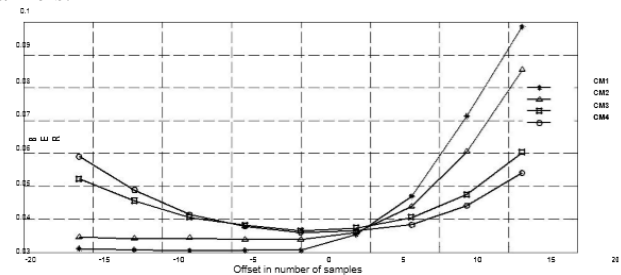


Fig. 5. Offset sensitivity of BER for all channel models at 10 dB  $E_b/N_0$  with fixed (32 samples) ‘ZP\_LEN’.

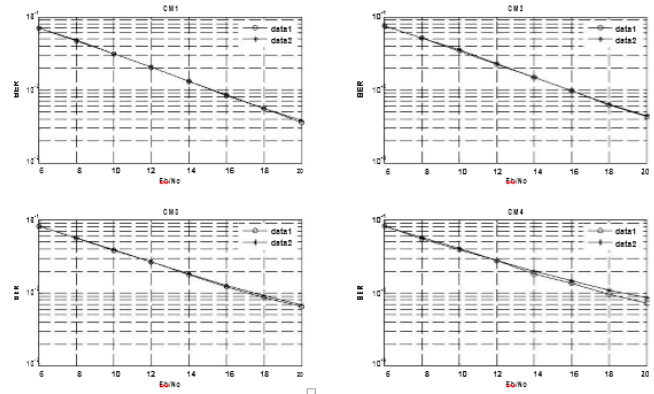


Fig. 6. BER vs  $E_b/N_0$  (in dB) simulation for all channel models in uncoded MB-OFDM system. Data1: using variable ZP length. Data2: Using fixed ZP length of 32.

#### 6. Conclusion

It is shown in this paper as well as in some prior arts that adaptive overlap-add technique is beneficiary for OFDM based receivers in terms of BER performance. In some related literature [9], it had been proposed to adapt ‘ZP\_LEN’ for overlap-add operation depending on the true channel length in order to avoid picking up pure noise samples during the OLA process. This method is more fruitful to channels having small delay-spread (e.g. CM1) and hence a small estimation error in FFT window will eventually reduce the benefit significantly. Moreover in [9], two independent process runs. One is

estimation of the channel delay spread and the other is estimation of FFT window. Both of them are used in adaptive OLA process and hence may make things worse instead of improving if they are not aligned properly. In an alternative, in this paper, we have proposed a band-dependent adaptive OLA technique which tries to minimize ISI incursion from subsequent OFDM symbols. This method is not so sensitive on the estimation of true start point of FFT window, in a sense that a small estimation error will not be able to take away the benefits of the technique. Moreover in this method all the signal processing is dependent on one independent process i.e. estimation of the FFT window and hence the question of dependency of two independent process does not arise at all. The method is more promising for large delay spread channels and provides a significant  $E_b/N_0$  improvement in the detection process. A natural choice of future work would be to mix the above two independent ideas (i.e. one in [9], and the one proposed in this paper) and study its impact on overall system performance.

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