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CP-FREE OFDM FOR FUTURE WIRELESS COMMUNICATION SYSTEMS

Faculty of Information Technology and Communication Sciences
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ABSTRACT

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Orthogonal frequency division multiplexing (OFDM) is a multicarrier transmission scheme and has been widely used in communication systems due to the advantages like simpler equalization, flexible signal arrangement and so on. Also, wireless communication can provide high data speed in cellular systems, which makes internet connection via mobile and other user equipment the primary approach in daily life. The existing long term evolution (LTE) and fourth-generation (4G) systems use OFDM as a downlink scheme and provide very high peak data speed. However, the development of user equipment (UEs) operating with high data rates and the continuously growing number of users creates needs for more features and high capacities for wireless communications. For meeting the needs of the latest and future applications, fifth-generation (5G) technologies are under intensive research and development, while the first phase of 5G is actively deployed by the operators. Those technologies aim to reduce the latency, reduce the power consumption, improve the throughput and support more users. In addition, the usage of 5G technologies can be categorized into three branches: enhanced mobile broadband (eMBB), ultra reliable low latency communication (URLLC) and massive machine type communication (mMTC). Because of the high spectral efficiency and other advantages of OFDM, it is still seen as a suitable modulation technique for 5G wireless communication applications. The most common OFDM scheme is CP-OFDM, which can cancel inter symbol interference (ISI) and ease the equalization process. However, the use of cyclic prefix (CP) introduces overheads which reduce the spectral efficiency and increase power consumption and latency. To meet the requirements of low latency and spectral efficiency in 5G New Radio (5G NR) applications, avoiding the usage of CP would be an interesting possibility if it could be done without severe drawbacks. This thesis provides one novel CP-free method called modified CP-free OFDM which can be used in 5G single input single output (SISO) communication. Comparing with existing CP-free designs, it does not require complex equalization algorithms or extra procedures for receivers' detection process. Also, it can achieve similar performance with conventional CP-OFDM with minor modifications on the receiver side with respect to basic CP-OFDM receiver. In the experiment part of the thesis, the modified CP-free OFDM was tested under TDD SISO communication scenarios with line-of-sight (LOS) and non-line-of-sight (NLOS) channel models, considering both, normal and pre-equalized configurations. Simulations are used to evaluate different variants of the scheme regarding the three main performance aspects: bit-error-rate (BER), peak-to-average power ratio (PAPR), and power spectral density (PSD) of the transmitted signal.

Keywords: OFDM, 5G NR, spectral efficiency, SISO, cyclic prefix (CP), latency

PREFACE

The research was started from the beginning of 2019 with the idea about CP-free OFDM given by my supervisor Prof. Markku Renfors. Thanks for his patience, encouragement and professional instructions, the problems and difficulties accrued during my thesis work are solved successfully. Also, i'm grateful for Prof. Markku, D. Sc Toni Levanen and Asst. Prof. Bo Tan. who spend their time in the weekly meeting to give me suggestions and corrections about research and academic writing.

In addition, i would like to thank my best friends Mohammad Ali Pourabed and Yuchuan Fan for their kindness help and encouragement in the past two years. Thanks to my parents for their supporting and everyone who helped me in my life.

Tampere, 13th November 2019

Sun Bo

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LIST OF SYMBOLS AND ABBREVIATIONS

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G-NR	5G New Radio
CDMA	Code Division Multiple Access
CIR	Channel Impulse Response
CP	Cyclic Prefix
DFT	Discrete Fourier Transform
DL	Downlink
F-OFDM	Filtered Orthogonal Frequency Division Multiplexing
FBMC	Filter-Bank Multicarrier
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FO	Frequency Offset
GFDM	Generalized Frequency Division Multiplexing
GPS	Global Positioning System
GSM	Global System for Mobile Communications
IBI	Inter Block Interference
ISI	Inter Symbol Interference
LSI	Large Scale Integration
LTE	Long Term Evolution
MCM	Multicarrier Modulation
MMS	Multimedia Message Service
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access

OOBE	Out-of-Band Emission
PAPR	Peak-to-Average Power Ratio
PRB	Physical Resource Block
SC-FDMA	Single-carrier FDMA
SCSE	Symbol Cyclic Shift Equalization
SISO	Single-Input and Single-Output
SMS	Short Message Service
TDD	Time-Division Duplex
TDMA	Time Division Multiple Access
TO	Time Offset
UL	Uplink
UMTS	Universal Mobile Telecommunications System

1 INTRODUCTION

Communication technologies have been developed rapidly in the past few decades from analog modulation-based communication systems to digital modulation-based communication systems, which may be combined with additional new elements like artificial intelligence (AI) and Big Data. The first-generation (1G) cellular mobile standards were made in 1981, three years after the development of the mobile communication system basics in Bell labs. During that time, each country had its own communication system and all mobile communication systems were based on frequency division multiple access (FDMA) and analog modulation [1] [2]. Ten years later, the second-generation (2G) communication system called global system for mobile communications (GSM), which provides voice call and extra short message service (SMS) function, began to be applied globally. From 2G, digital communication started to be used and became dominant in the later communication systems because of the high security of digital communication [1]. After 2G, also time division multiple access (TDMA) and code division multiple access (CDMA) principles were adopted to mobile communication systems. In order to meet the needs for higher cellular communication transmission speed, wideband code division multiple access (WCDMA) technology-based universal mobile telecommunications system (UMTS) was introduced by the 3rd generation partnership project (3GPP) in early 2000s. UMTS can not only provide multimedia message service (MMS) but also let watching video on mobile became possible [3]. The main features of the third generation system (3G) are video calls, broadband communication applications like mobile television, and other high data speed audio or video services. Long term evolution (LTE) was started as the revolution of UMTS, and its later version LTE-Advance fulfills the requirements of the fourth-generation system (4G). 4G can provide 100 Mbps throughput [4] which supports high-quality video streaming [5]. However, the demands for more efficient and higher throughput communication still cannot be met by LTE. To further develop the wireless communication system, 3GPP began to set the schedule and goals of a new radio-access technology in the fall of 2015. According to 3GPP Rel15 and 16, making fifth-generation system (5G) standards is executed in three stages and it starts in 2016 till the beginning of 2020 [4]. 5G NR is an orthogonal frequency-division multiplexing (OFDM) based new air interface, and 3GPP deployed it for the mobile communication network. It is a new radio access technology for next generation cellular communication networks. Also, 5G new radio (5G NR) will not backward compatible to old networks anymore [4][6].

From 4G to 5G, OFDM plays an important role in mobile communication networks since it is an efficient solution for high data speed mobile communication applications. Also, it can combine diversity, space-time block code and smart antenna to further improve the system capacity. OFDM has several drawbacks such as high out of band emission (OOBE), high peak to average power ratio (PAPR) and it is sensitive to time offset (TO) and frequency offset (FO). Also, the use of cyclic prefix (CP) extends the length of the signal, which generates latency of signal transmission and also reduces the transmission efficiency. To further adapting OFDM into 5G NR applications to meet the low latency requirement, reducing the OFDM signal transmission latency is the key point to explore.

In this thesis, single input single output (SISO) time-division duplexing (TDD) based CP-free OFDM scheme is considered as a proper solution for improving the spectrum efficiency and power efficiency and reducing transmission latency efficiently. Our design is based on the idea of CP-free OFDM method published by Hamamreh et al. [7]. This makes it possible to transmit OFDM signal without using CP. The main idea is to add an alignment signal to the transmitted waveform, which can provide circularity of the received waveform without CP in case of a frequency-selective multipath channel. Then the basic OFDM channel equalization model is still applicable for the receiver. To further enhance the performance and improve the efficiency, frequency domain alignment signal generation method is developed in this thesis. Our modified CP-free OFDM generates the alignment signal by the frequency domain calculation rather than the time domain calculation used in Hamamreh et al. method. This improves the calculation accuracy and functionality of alignment signal by avoiding the calculation of pseudo inverse matrix of channel convolution matrix. Also, modified CP-free OFDM significantly improves the spectral efficiency without changing the simple equalization procedure used in conventional CP-OFDM. We test the new method with two 5G channel models, TDL-C and TDL-D with different channel delay spread parameters, under conventional TDD communication scenario and pre-equalized TDD communication scenario. Also, because the alignment signal generation procedure relies on channel knowledge on the transmitter side, a CP-OFDM based channel sounding procedure is included in the simulation setup. Then we explore the channel sounding influence with the comparison of pilot boosting channel sounding and normal channel sounding. What's more, the performance of modified CP-free OFDM is explored with higher QAM modulation order and different excess bandwidths in channel sounding.

The rest of this thesis is organized as follows. The background of OFDM and 5G with its waveforms are discussed in Chapter 2. The methodology of basic and modified CP-free OFDM are explained in Chapter 3. Chapter 4 discusses the implementation of modified CP-free OFDM and Chapter 5 reports analyses the simulation results. Finally, conclusion and future work are summarized in Chapter 6.

2 OFDM AND CELLULAR COMMUNICATION SYSTEMS

2.1 Historical background of OFDM

OFDM has been developed for more than 60 years, the beginning of OFDM is MCM (multicarrier modulation) used by the USA army for reducing the ISI between channels. In 1971, Weistein and Ebert developed a multicarrier system based on DFT and FFT, and they named it OFDM system. This system reduced the complexity of OFDM structure and solved the problems of recovering multiple orthogonal subcarriers on the receiver side. However, OFDM system did not get enough attention in RF communication systems because of lack of powerful equipment and chips to support the complicated calculation of FFT at that time. Till the 1980s, the developing of LSI (Large Scale Integration) technology made complicated FFT processing possible in real time. Cimini suggested to apply OFDM technologies to communication area in 1985. After that, OFDM technologies were developed rapidly and OFDM became one of the main modulation schemes in wireless communications. New IEEE802.11 and 802.16 standards selected OFDMA as the modulation approach in 2001. Besides that, 3GPP chose OFDMA and SC-OFDMA for LTE downlink and uplink respectively. In the future, OFDM will still be the main modulation technique for 5G communication systems according to the 3GPP 38 recommendation series [8][9][10].

2.1.1 OFDM waveform

OFDM is a multicarrier transmission technique which divides the whole signal band into multiple small parts and sends those narrowband signals simultaneously. When compared with conventional single carrier modulation, OFDM converts high-rate data stream into several low-rate data streams, which can be modulated separately with different modulation schemes. Conventional single carrier modulation schemes are vulnerable against ISI, and multipath propagation of single carrier modulation in rayleigh fading channel would generate extra errors. Different from FDM, OFDM uses orthogonal subcarriers to carry information rather than use guard band to reduce the ICI between subcarriers, which improves the spectral efficiency of OFDM. Mathematically, the spectrum of OFDM subcarriers is a serial of impulse functions for active subcarriers and zeros for non-active subcarriers. Ideally, each subcarrier does not have influence on other subcarriers, called

Intercarrier Interference (ICI). In reality, OFDM signal is transmitted in a block scheme, the length of each block is settled beforehand. Because of that block transmission scheme, OFDM signal is physically windowed by rectangular pulses in the time domain. The Fourier transform of the rectangular pulse is sinc pulse and those sinc pulses are partially overlapping with each other. However, this specific choice of subcarrier spacing provides orthogonality of subcarriers. The figure 2.1 shows OFDM signal spectrum in the transmitter side, subcarriers are orthogonal to each other but sidelobes can be found in the specific time instant. Once the time domain symbol length is known, we can get the subcarrier spacing via $\delta f = \frac{1}{Tu}$, where T_u is the symbol duration [11].

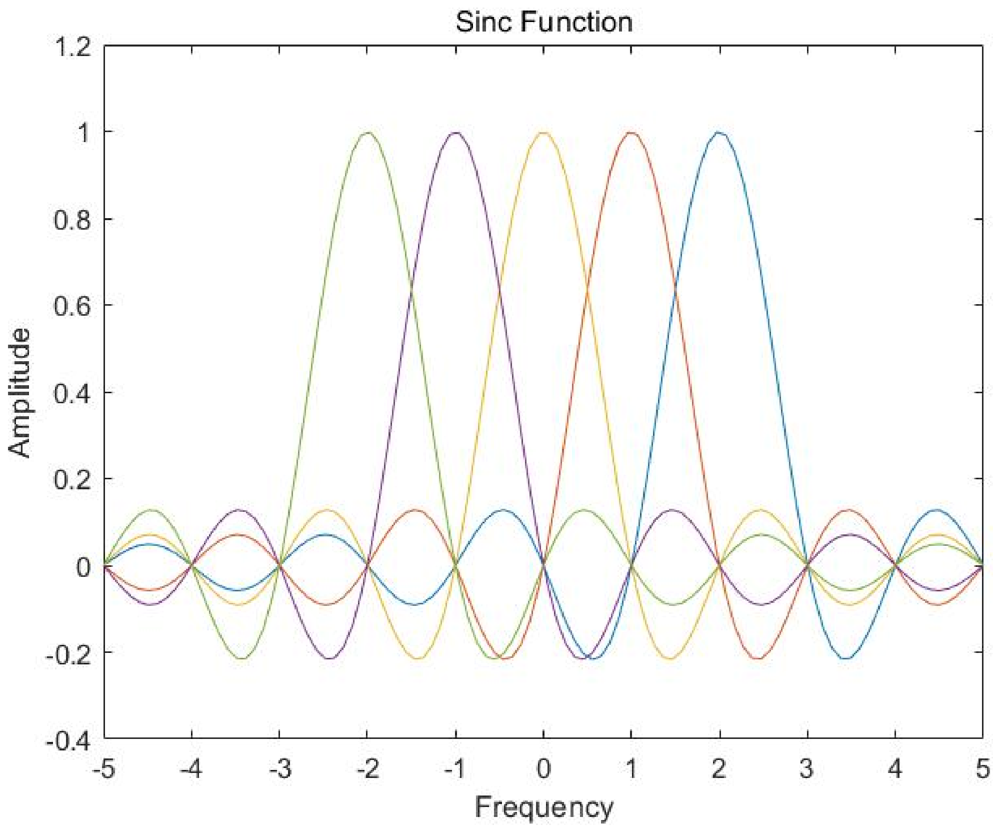


Figure 2.1. *OFDM signal spectrum*

2.1.2 OFDM transmitter and receiver structures

The structures of OFDM receiver and transmitter are shown in figure 2.2. For clearly understanding how OFDM signals are generated and detected, let's assume that a block N complex data symbols A_0,A_1,....,A_{N-1} needs to be transmitted. Firstly, zero values are added at the beginning and end of the symbol sequence before the symbols are modified by a IFFT block. Those zeros used as guard band for reduce the interference leakage between the information signals and other signals located at neighbor band. The total length of symbols equals to N + N_zero, and it is selected as a power of two, for example, 64, 256..., so as to adopt fast furious transform for OFDM modulation for reducing the calculation complexity. Secondly, the transform of data symbols from the frequency domain to time domain is achieved by the IFFT block which equivalent a bunch of complex modulators [12]. The last step before sending OFDM signal is adding CP at the beginning of each time domain symbol, which used to providing circularity to signal.

As equation 2.1 shows, all complex symbols are summed together in time domain after passing the IFFT block, where N is the IFFT length and A_k is the kth signal which is modulated on the kth subcarrier.

$$x_k = \sum_{k=0}^{N-1} A_k e^{j2\pi\Delta f_k t} \tag{2.1}$$

The receiver of OFDM systems has symmetric procedures with the transmitter. It discards CP right after the signal detection process, then passes the signal through FFT block to recover frequency domain symbols. After removing the non-active subcarriers, the one-tap equalizer is adopted in data symbols to eliminate attenuation and distortions incurred by the propagation of the signal.

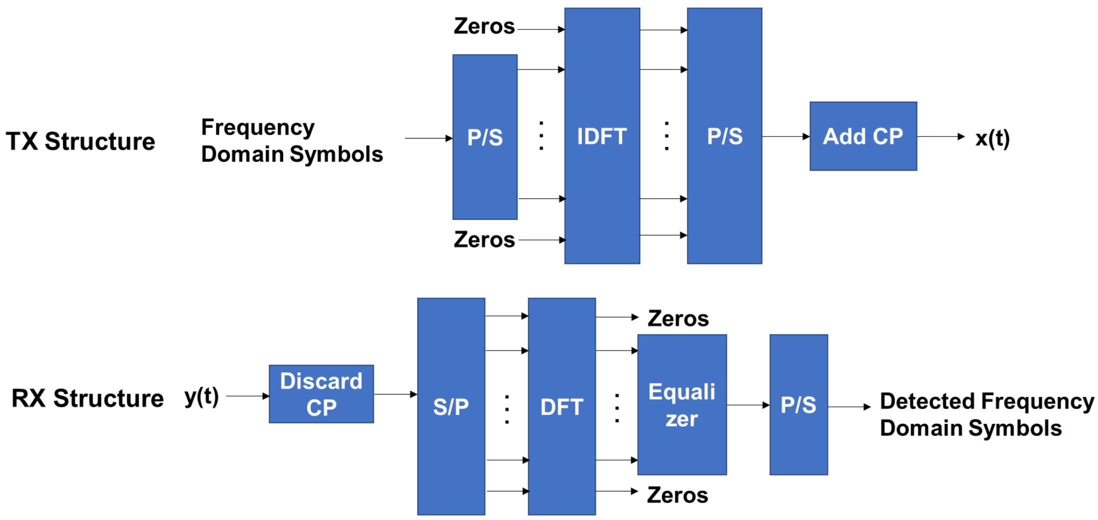


Figure 2.2. *OFDM system structure*

2.1.3 OFDM and CP

Multipath influence is a vital issue for OFDM signal recovering since it will generate ISI and ICI between contiguous symbols and which will lead to high bit error-rate (BER) [13][14]. For keeping the orthogonality of OFDM symbols, CP is inserted between symbols [13]. CP is a copy of the original symbol end part which placed onto the beginning of symbols. As figure 2.3 shown, the signal comes from two paths would reach the receiver at different times, and ISI will occur between symbols.[15]. As long as CP longer than maximum channel delay, the orthogonality between OFDM subcarriers can be protected. In the mathematical aspect, the convolution of two infinite periodic signals can be calculated in the frequency domain as the multiplication of two signals' Fourier transform. However, the raw OFDM signal received by the receiver does not fulfill Fourier convolution standards and frequency domain symbols cannot be simply separated from channel frequency impulse response since the received signal is not infinite periodic signal. CP, an excellent and simple design, makes symbols and CIR circularly convoluted in the time domain, and if two discrete signals are circularly convolved, then the DFT transform of two signals are multiplied. Thus, OFDM symbols and CIR can easily be separated in the frequency domain with the help of CP.

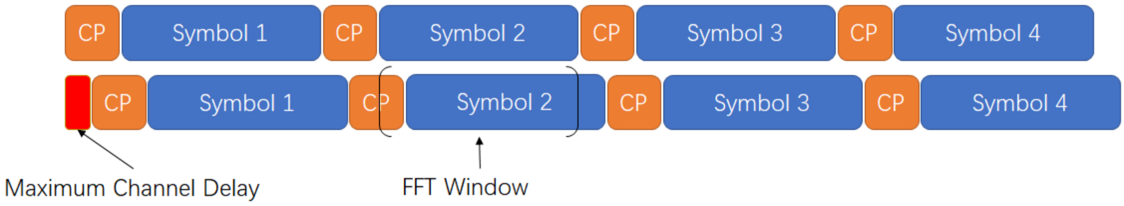


Figure 2.3. *Multipath Influence*

2.1.4 Disadvantages

OFDM is a functional modulation scheme with high spectrum efficiency and good robustness against channel frequency selectivity [16]. However, OFDM has several drawbacks in reality. High PAPR is one problem of OFDM. OFDM signal is composed of multiple carriers in the time domain, and that could lead to high signal values at a specific time. Amplifier can amply signal strength with fixed times when the amplitude of input signal located in the amplifier's linear region, the longer linear region the amplifier has the more power it consumed [17]. Thus, the equipment which does not have enough power supply cannot support OFDM system. There are several technologies to combat this drawback. For example, LTE uses SC-FDMA as the uplink modulation approach and it changes the multicarrier signal into a single carrier signal and significantly reduces the PAPR.

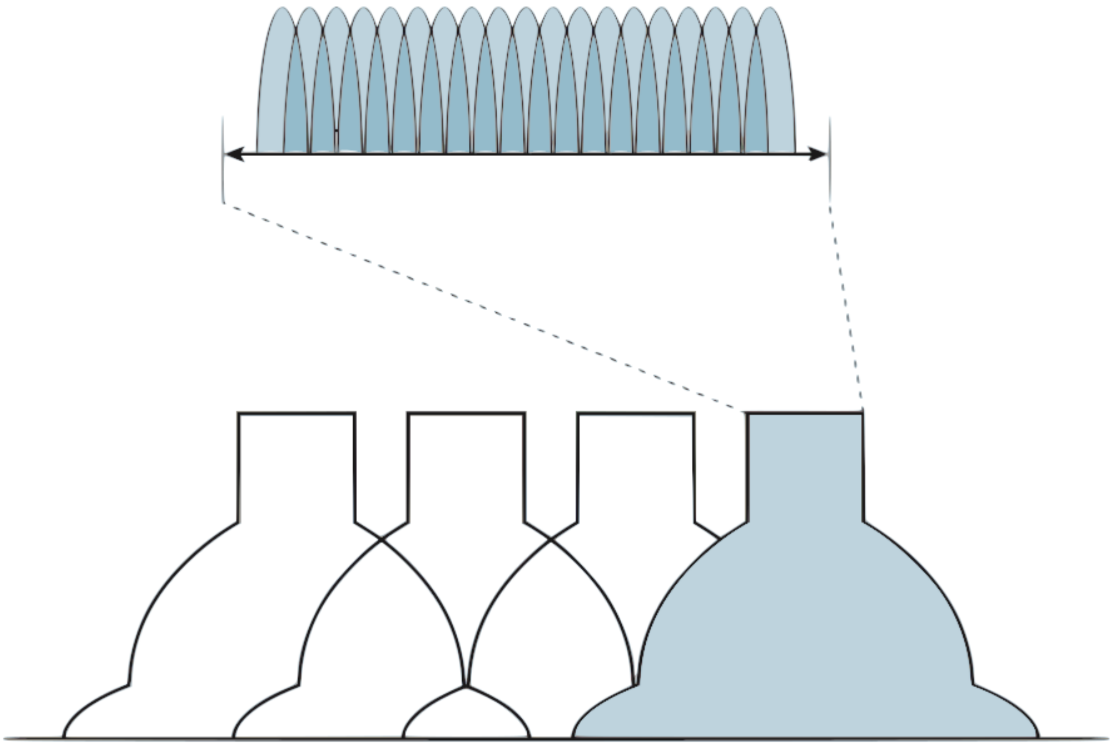


Figure 2.4. *OFDM subcarriers spectrum and spectrum of multiple OFDM channels.*

From figure 2.4, we can see the sidelobes of OFDM signal leaked to the neighbor band, which is another drawback of OFDM. Each OFDM block contains subcarriers and guard band which is used for reducing IBI, but the sidelobes of each OFDM channel still have signal leakage. Thus, OOBE is one problem for adapting OFDM in future communication systems [18] and there are many multicarrier transmission schemes aiming to reduce the OOBE such as filter-bank multicarrier (FBMC), generalized frequency division multiplexing (GFDM) and filtered orthogonal frequency division multiplexing (F-OFDM) [19][20][21].

Usage of CP can provide advantages for combating ISI but it will extend the length of symbols. The extra extension of symbols reduces the overall data rate and the system capacity and the loss of spectral can go up to 25% due to the use of CP in some applications [22][23].

2.2 OFDM with LTE

OFDM/FDMA is the core technique of 4G mobile communication system. The main objectives of LTE include: providing minimum 100 Mbps and 50 Mbps peak data speed in DL and UL, respectively with 20 MHz spectrum, improve the capacity, reduce delay to less than 5 ms. LTE uses different OFDM techniques for UL and DL because of the high PAPR problem for UE. OFDMA is used in DL, this technique separate time and frequency domain into multiple slots to use time and frequency resource flexibly for different users, it can be seen as the combination of FDMA and TDMA. The basic unit of LTE air interface resource is a physical resource block (PRB). As figure 2.5 shown, one PRB is combined by 12 continues frequency subcarriers and 7 continuous symbols in the time domain, in another word, 84 Resource Elements are contained in one PRB. [24][25][26] Every single RE can use different modulation orders from QPSK, 16-QAM, and 64-QAM, the selection of modulation order depends on the wireless environment.

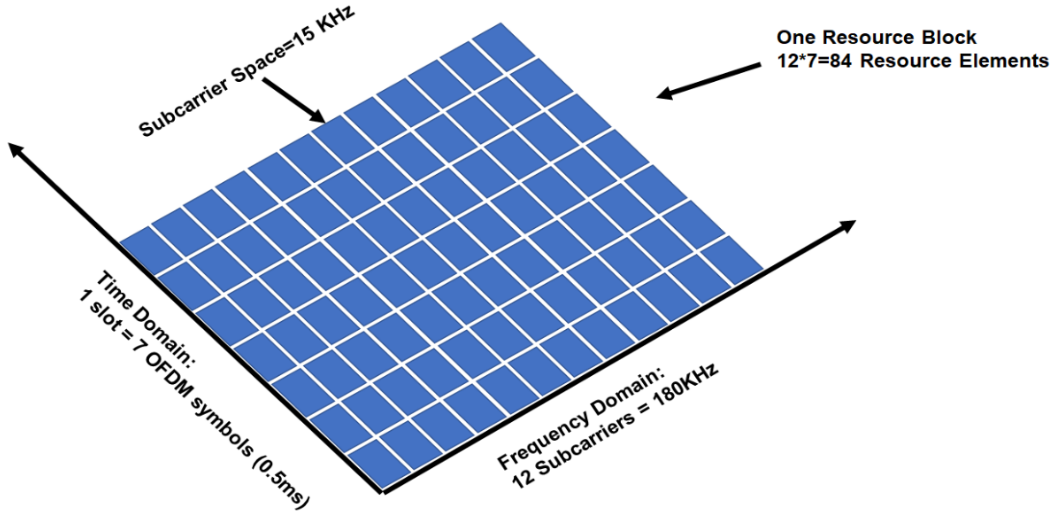


Figure 2.5. *LTE Resource Block*

For reducing the power consumption and cost of power amplifiers in the UE side, SC-FDMA is adapted as a UL modulation technique. SC-FDMA uses extra DFT block to change signal from the time domain to the frequency domain before sending the signal into IFFT block to generate a single carrier signal to avoid high PAPR. This technique has lower spectral efficiency than OFDMA but it still much higher than traditional FDMA techniques. Same with OFDM, SC-FDMA will allocate frequency resources base on the needs of user and system resource allocation schemes. Also, SC-FDMA does not require a guard band which used in conventional single-carrier techniques, since the frequency subcarriers are orthogonal to each other [24]. Moreover, post-processing can be adapted to OFDM signal, such as adding window function in the time domain or filter in the frequency domain, which can provide more features to OFDM signal. Thus, multiple different OFDM schemes working in the same band became possible.

2.3 OFDM with 5G

As the next-generation cellular communication system, 5G NR is developed for supporting wireless communication between various devices, diverse service and many different deployment scenarios in the next ten years. Also, the aim of 5G is fully utilizes the spectrum for higher data speed and spectral efficiency. According to Qualcomm's report, optimized OFDM-based waveforms and multiple access, orthogonal frequency division multiplexing, a flexible framework, advanced wireless technologies are necessary for building 5G NR. [27] The most important decision of 5G NR design is optimized OFDM-based waveforms and multiple access since OFDM techniques have been widely used in LTE and Wi-Fi communication systems. Thus, OFDM can be further applied in higher and wider spectrum use cases. Also, the high spectral efficiency and low complexity let OFDM became the most suitable waveform for 5G applications [28].

2.3.1 5G applications

According to ITR-U's recommendation about IMT, as figure 2.6 shown, 5G applications would have three main usage scenarios which are eMBB, URLLC and mMTC [29][30]. With the help of eMBB, existing wireless communication systems' throughput can be significantly improved and support seamless communication services. Also, eMBB could accelerate the exploration of a new area and the demands of wireless applications. For example, the gigabytes transmission of mobile communication would let 3D video and VR live streaming became accessible on mobile and downloading high qualify movies cost extremely less time than existing 4G systems. The eMBB contains multiple transmission schemes, such as wide coverage and hot spot. For wide coverage case, seamless coverage and stable service for fast speed moving communication are the most important demands. Meanwhile, the data throughput of wide coverage should be higher than the throughput of 4G communication. The hot spot aims to provide service for a small area that has a high device density. For example, the center of urban have more clients who need higher transmission speed than wide coverage case and have low mobility. The predicted throughput of eMBB is 20 Gbit/s for downlink and 10 Gbit/s for uplink [31][30]. The URLLC aims to provide high transmission speed with extremely low latency for applications which related to emergency situations. For example, smart driving cars, remote medical surgery and automated industry are perusing fast, dependable and safe communication which has latency less than 1 ms [32]. With the developing of factories and cities, the number of devices linked to communication systems is increasing drastically. Thus, mMTC is developed for supporting future Internet of things applications. In mMTC scenarios, low cost and durability are the two most important issues for machine type communication, since a large number of devices used in industries and factories, such as sensors or meters, will connect to the system. Challenges involved in this case are how to extract signals correctly from a vast number of resources and how to make sure the devices can work in a long period, several years for example.

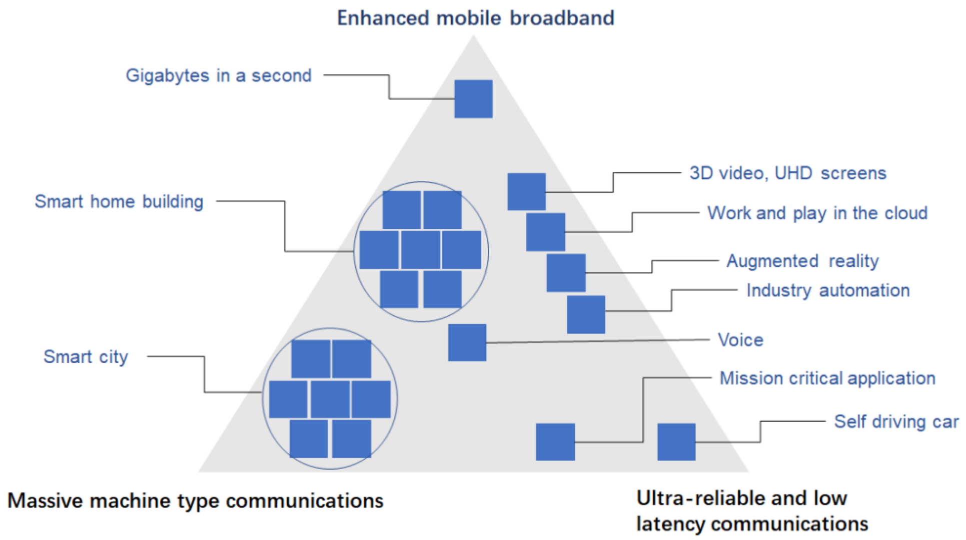


Figure 2.6. *IMT-2020 use cases and usage scenarios*

2.3.2 OFDM numerology in 5G

5G leads the trend of wireless communication to a new era where humans and items are linked via radio communication and information can be transmitted anywhere and anytime. For supporting the 5G NR systems, wider spectrum is needed besides new functionalities. Figure 2.7 illustrates the spectrum from 2G to 5G communication systems. The used spectrum of commercial cellular communication systems is below 6 GHz, such as GSM, CDMA, and LTE. There are some local area networks and indoor communication systems based on the IEEE 802.11ad and 802.15.3c standards that operate in the unlicensed 60 GHz band. For improving and exploring the ability of radio communication systems, 3GPP provided 5G standards that announce the operating spectrum is located between 1GHz to 100 GHz [30][26][33].

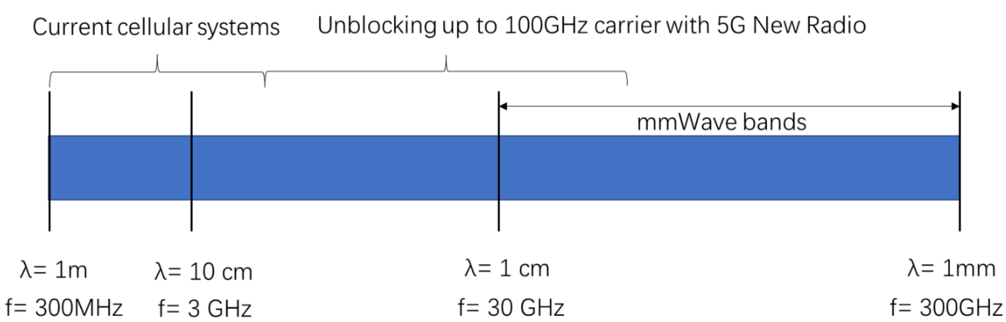


Figure 2.7. *Frequency ranges of current and future mobile communication systems.*

For fitting the requirements of 5G NR, the configuration of OFDM need to be changed in the future systems. LTE currently uses the subcarrier with 15kHz wide, 5G will expand the subcarrier space to keep the calculation complexity the same as before while the system has wider bandwidth. As table 2.1 shown, the OFDM subcarrier space in 5G systems have mainly four categories. The first scenario is outdoor and macro coverage, which working in the spectrum less than 3 GHz with FDD or TDD model, the subcarrier spacing of that case is 15 kHz. The second scenario is outdoor and small cell, the subcarrier space is 30kHz and working between 3 GHz to 5 GHz. Indoor wideband is the third scenario for 5G, 60 kHz is selected for those communication systems working in the unlicensed spectrum which located in 5 GHz. The last scenario is set for system working beyond 5 GHz, for example, 120 kHz is the subcarrier space while the system working in 28 GHz [27].

Table 2.1. *Numerology of OFDM signal*

Subcarrier spacing	15kHz	30kHz	60kHz	15×2^nkHz
OFDM symbol duration	$66.67\mu s$	$33.33\mu s$	$16.67\mu s$	$\frac{66.67}{2^n}\mu s$
Cyclic prefix duration	$4.69\mu s$	$2.34\mu s$	$1.17\mu s$	$\frac{4.69}{2^n}\mu s$
OFDM symbol including CP	$71.35\mu s$	$35.68\mu s$	$17.84\mu s$	$\frac{71.35}{2^n}\mu s$
Number of OFDM symbols per slot	14	14	14	14
Slot duration	$1000\mu s$	$500\mu s$	$250\mu s$	$\frac{1000}{2^n}\mu s$

2.4 CP reduction techniques

Although OFDM is widely used waveform in many existing communication systems and is expected to keep its dominance in future 5G systems, its performance in terms of spectral efficiency as well as transmission latency is usually degraded due to the excessive usage of CP. Especially under high dispersive channels, CP length is expended to guarantee frequency domain equalization working properly. To meet the requirement of low transmission latency and high spectral efficiency in the 5G communication system, there are many CP reducing methods researched and published.

Recently, a CP-free OFDM scheme was proposed based on symbol cyclic shift equalization (SCSE) algorithm and PAM modulation. It is denoted as SCSE PAM-OFDM algorithm. This design turns linear convoluted CP-free OFDM signal into a cyclic-shifted signal before FFT block on the receiver side. What's more, the calculation of algorithm only needs partial samples of OFDM signal so as to reducing calculation complexity [34][22].

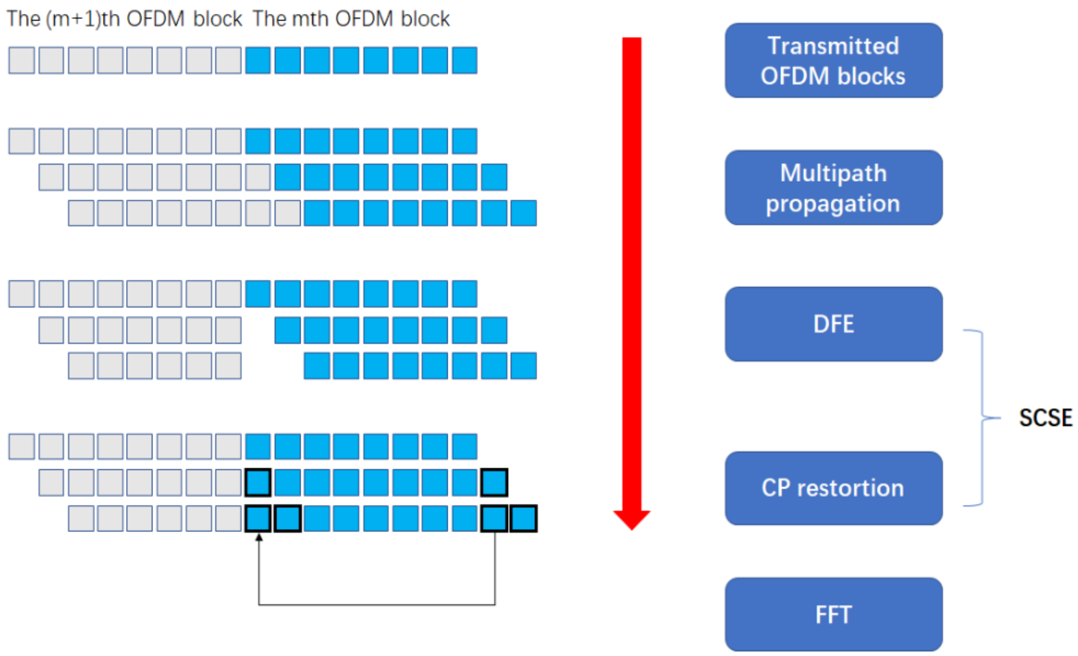


Figure 2.8. *Block diagram of an SCSE PAM-OFDM receiver*

Figure 2.8 shows the working process of the SCSE PAM-OFDM receiver. Signal passed through the multipath channel will have ISI which is canceled by DFE and CP restoration block can put circularity providing signal into the beginning of each signal block. However, the noise strength in CP restoration part heavily influences the performance of SCSE PAM-OFDM. In addition, the delay of equalizer and CP restoration can lead to error detection and the error rate can be high if channel coding is combined [31].

CP reduction for low-latency wireless communications in OFDM Javier et al. [35] provided a CP reduction approach which minimizing time domain resources consumption of CP by slightly increasing the detection complexity at the receiver. The time transmission interval (TTI) structure they proposed to use one single OFDM symbol with CP as the beginning and concatenates that CP-OFDM symbol with multiple row OFDM symbols without adding CP. Figure 2.9 depicts the signal structures of regular CP-OFDM and proposed TTI. Thus, the transmission efficiency is increased to n=Ncp/(Ncp+Nsym*Nofdm), where Nsym is the number of OFMD symbols in a TTI. As figure 2.10 shown, the proposed TTI structure generates the first symbol as same as regular OFDM, but the later symbols are combined as one enlarged OFDM symbol containing the concatenated subcarriers of the original remaining (Nsym-1) OFDM symbols and the corresponding length in the time domain [35]. The main advantage of the proposed TTI structure is it improves the efficiency of handling ISI and ICI while not influence the maximum OFDM CFO tolerance to compare with regular CP-OFDM structure.

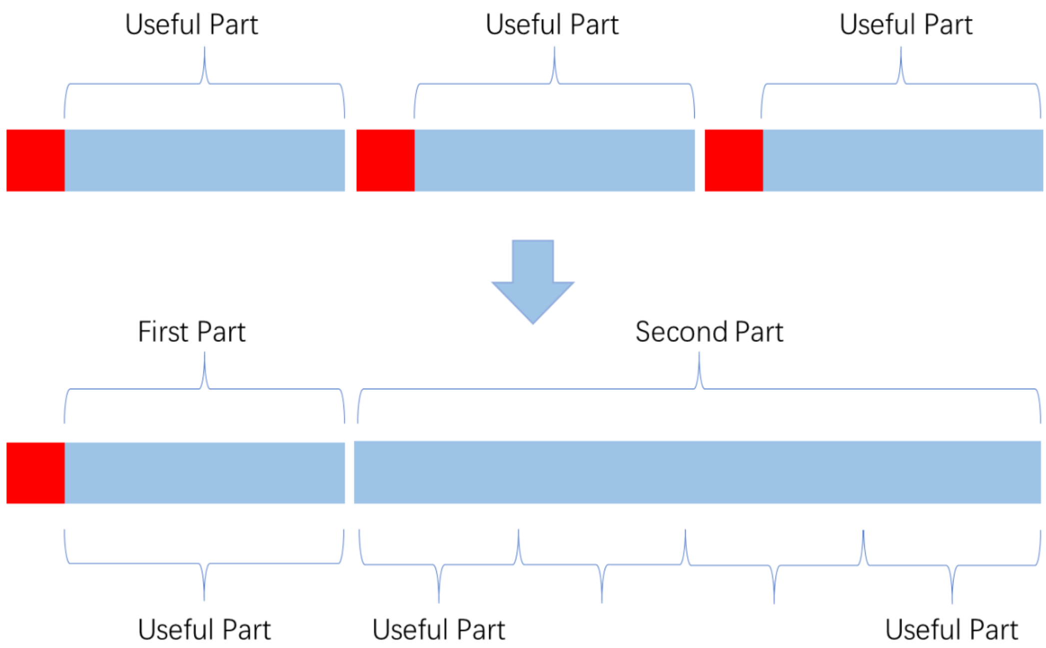


Figure 2.9. *TTI structure*

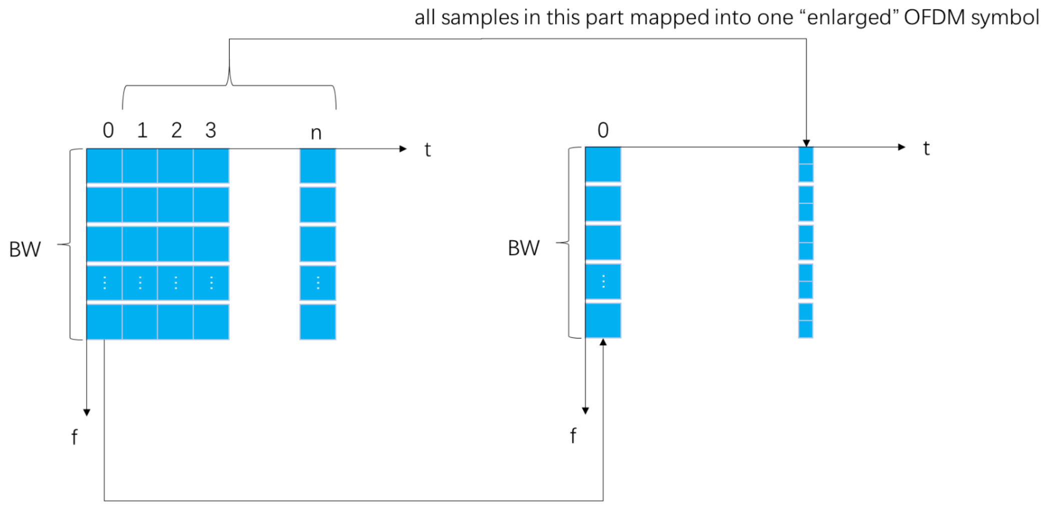


Figure 2.10. *Illustration of the mapping process of complex symbols to time frequency resources*

The proposed TTI structure and detection algorithm reduce CP overhead and keeping the simple processing at the receiver. With the different detection scheme for the first symbol and enlarged OFDM symbols, the spectral efficiency and throughput increased.

Hamamreh et al. [7] proposed a novel power domain-based OFDM scheme, which totally removes the procedure of adding CP in OFDM symbols and maintains the detection process of receivers under the assumption of a SISO OFDM communication scenario. Figure 2.11 compares transmitter and receiver structures of regular CP-OFDM and CP-free OFDM. Instead of adding CP in the transmitter, their scheme generates new a new additive signal element, which is called alignment signal. That signal is added on top of the original symbols and sent with original symbols simultaneously. The CP-free scheme of Hamamreh et al. [7] has two variants, CP-Free OFDM and ZP-Less OFDM, which based on CP-OFDM and ZP-OFDM systems respectively. Those two methods assume the knowledge of the multipath channel taps in advance, and then calculate the convolution matrix of the channel to generate the alignment signal. The mathematical details will be explained in Chapter 3. The difference of the two approaches is how the ISI canceling signal and circularity providing signal are arranged and where they come from. The AS used in the CP-less is based on the ISI coming from the previous symbol, but ZP-less OFDM with overlap addition (OLA) generates AS based on the ISI coming from each symbol itself [7]. CP-free OFDM design gives a suitable waveform candidate which meets the needs of high spectral efficiency, high power efficiency, low latency and communication security in 5G and beyond communication applications. In addition, their method keeps the merits of easier equalization procedures in regular CP-OFDM while canceling the ISI between symbols and providing circularity with a simple procedure. However, the accuracy of channel estimation and errors come from the pseudo inverse of the channel convolution matrix, and it influence performance of the aforementioned CP-free OFDM. Moreover, the influence of convolution matrix accuracy were not explored in detail. What's more, the modulation scheme and channel model used in their simulations need to be replaced by more complicated schemes to evaluate whether they are suitable in real cases.

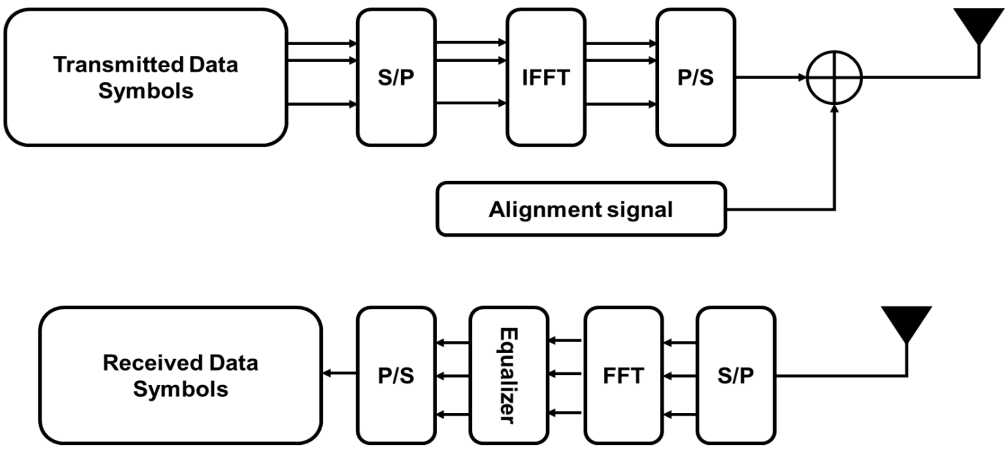


Figure 2.11. *Transmitter and receiver structures of the CP-free OFDM*

3 METHODOLOGY

This chapter will first explain how CP provides circularity to OFDM signals and cancels ISI introduced by the multipath channel. After that, Hamamreh's CP-free OFDM is analyzed based on the knowledge of CP and and the channel matrix with Toeplitz structure. Finally, a novel new OFDM scheme, called modified CP-free OFDM, will be fully explained.

3.1 Toeplitz Matrix, Circulant and Convolution

To fully understanding how the multipath channel influences the signal, the Toeplitz matrix structure needs to be known first. Consider an $n \times n$ matrix having constant elements on each descending diagonal from left to right is constant, i.e., a matrix of the form

$$T_n = \begin{bmatrix} c_0 & c_{-1} & c_{-2} & \cdots & c_{-(n-1)} \\ c_1 & c_0 & c_{-1} & & \vdots \\ c_2 & c_1 & c_0 & & \vdots \\ c_3 & & & & \\ c_{n-1} & & \cdots & & c_0 \end{bmatrix} \tag{3.1}$$

We call matrix (3.1) Toeplitz matrix, which is widely used in many areas like physics, mathematics, statistics, and signal processing. In digital communication context, Toeplitz matrix is used to calculate the output of a filter or multipath channel while input is discrete-time domain data. [36]

Circulant matrix of the form (3.2) is a special case of Toeplitz Matrix, which has a characteristic that every row of the matrix is a right cyclic shift of the row above it. [37] This matrix is used in the applications of CP-OFDM and cyclic codes for error detection.

$$C_n = \begin{bmatrix} c_0 & c_{-1} & c_{-2} & \cdots & c_{-(n-1)} \\ c_{-(n-1)} & c_0 & c_{-1} & & \vdots \\ c_{-(n-2)} & c_{-(n-1)} & c_0 & & \vdots \\ \vdots & & & & \\ c_{n-1} & c_{-2} & \cdots & & c_0 \end{bmatrix} \tag{3.2}$$

Suppose we have a wireless communication system working with OFDM signal, which transmits four data symbols $[x_0, x_1, x_2, x_3]$, and the multipath channel has three taps which are $[c_0, c_1, c_2]$. Then the received signal from multipath channel can be expressed as following:

$$y = h_n x = \begin{bmatrix} c_0 & 0 & 0 & 0 \\ c_1 & c_0 & 0 & 0 \\ c_2 & c_1 & c_0 & 0 \\ 0 & c_2 & c_1 & c_0 \\ 0 & 0 & c_2 & c_1 \\ 0 & 0 & 0 & c_2 \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} P \\ S \end{bmatrix} = \begin{bmatrix} c_0 x_0 \\ c_1 x_0 + c_0 x_1 \\ \vdots \\ c_2 x_2 + c_1 x_3 \\ c_2 x_3 \end{bmatrix} \tag{3.3}$$

With entries

$$y_k = \sum_{i=0}^{k} c_{k-i} x_i \tag{3.4}$$

Equation (3.4) mathematically explains how multipath propagation influences the signal received by the receiver. The channel not only influences the signal amplitude but also introduces the delayed signal, which will become the interference on the later symbols. Practically, multipath influence can be compensated by a proper adaptive equalizer in the receiver side. Equalization can be done in time or frequency domain; time-domain equalization generally is more complex than frequency domain equalization since there is no accurate way to reverse the convolution matrix in the time domain. For example, the one-tap equalizer used in conventional CP-OFDM systems is a frequency domain equalizer used to compensate channel influence of each active subcarriers by a simple multiplication rather than complicated time domain equalizer. However, the one-tap equalizer used in CP-OFDM systems works well only if signal and channel are circularly convolved. The needed procedures for achieving cyclic convolution are just adding CP and dropping CP in the transmitter and receiver sides, respectively, while the CP length exceeds the maximum delay spread of the channel.

3.2 CP-OFDM, ZP-less OFDM, and modified CP-free OFDM

Continuing from the previous section, CP is an efficient way to combat ISI and provide circularity by extending the length of the signal. As we discussed in Chapter 2, CP is a partial copy of the original signal which is added at the begin of the signal. Suppose that a new signal X_{cp} is composed by signal X and CP of signal X, $X_{cp} = [x_2, x_3, x_0, x_1, x_2, x_3]$. Based on the equation (3.3), the convolution process of CP-OFDM signal is expressed by the equation 3.5.

$$y = h_n x = \begin{bmatrix} c_0 & 0 & 0 & 0 & 0 & 0 \\ c_1 & c_0 & 0 & 0 & 0 & 0 \\ c_2 & c_1 & c_0 & 0 & 0 & 0 \\ 0 & c_2 & c_1 & c_0 & 0 & 0 \\ 0 & 0 & c_2 & c_1 & c_0 & 0 \\ 0 & 0 & 0 & c_2 & c_1 & c_0 \\ 0 & 0 & 0 & 0 & c_2 & c_1 \\ 0 & 0 & 0 & 0 & 0 & c_2 \end{bmatrix} \begin{bmatrix} x_2 \\ x_3 \\ x_0 \\ x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} Q \\ W \\ S \end{bmatrix} = \begin{bmatrix} c_0 x_2 \\ c_1 x_2 + c_0 x_3 \\ \vdots \\ c_2 x_2 + c_1 x_3 \\ c_2 x_3 \end{bmatrix} \tag{3.5}$$

The result of the above equation can be divided into three parts, CP head (Q), circularly convoluted signal (W) and inter-symbol interference into later symbols (S). The CP head will be removed after the OFDM symbols received by the receiver, and ISI which length is determined by the maximum channel delay will locate at the beginning of next symbols. Thus, ISI can be canceled automatically by CP head removing procedure while CP is longer than maximum channel delay. After CP dropping, there is only circularly convoluted signal W left, as equation 3.6 shows. Signal and channel are circularly convolved in matrix W, and it fulfills the DFT characteristic for separating two-time domain convolved signals in the frequency domain.

$$W = \begin{bmatrix} c_2 x_2 + c_1 x_3 + c_0 x_0 + 0 + 0 + 0 \\ 0 + c_2 x_3 + c_1 x_0 + c_0 x_1 + 0 + 0 \\ 0 + 0 + c_2 x_0 + c_1 x_1 + c_0 x_2 + 0 \\ 0 + 0 + 0 + c_2 x_1 + c_1 x_2 + c_0 x_3 \end{bmatrix} \tag{3.6}$$

Continuing with the equation 3.5, the real CP head of received OFDM symbols can be expressed by equation 3.7. The interference coming from the previous symbol S_{n-1} will locate at the CP head Q_n, and that's the reason why dropping CP can cancel the ISI introduced by multipath propagation.

$$\begin{aligned} CP_n &= Q_n + S_{n-1} \\ &= \begin{bmatrix} c_0 x_2 + 0 + 0 + 0 + 0 + 0 \\ c_1 x_2 + c_0 x_3 + 0 + 0 + 0 + 0 \end{bmatrix} + \begin{bmatrix} 0 + 0 + 0 + 0 + c_2 x_2 + c_1 x_3 \\ 0 + 0 + 0 + 0 + 0 + c_1 x_3 \end{bmatrix} \\ &= \begin{bmatrix} c_0 x_2 + 0 + 0 + 0 + c_2 x_2 + c_1 x_3 \\ c_1 x_2 + c_0 x_3 + 0 + 0 + 0 + c_1 x_3 \end{bmatrix} \end{aligned} \tag{3.7}$$

CP-free OFDM published by Hamamreh et al. [7] aims to cancel ISI without using CP while keeping the circularity for recovering signal in the frequency domain. The alignment signal they generated from equation (3.3) and (3.7).

Comparing equations (3.6) and (3.3), if we add signal's ISI part into the beginning of the OFDM signal, then we can get a cyclically convolved signal:

$$P + S = W$$

$$\begin{bmatrix} 0+0+c_2x_2+c_1x_3 \\ 0+0+0+c_1x_3 \\ 0+0+0+0 \\ 0+0+0+0 \end{bmatrix} + \begin{bmatrix} c_0x_0+0+0+0 \\ c_1x_0+c_0x_1+0+0 \\ c_2x_0+c_1x_1+c_0x_2+0 \\ 0+c_2x_1+c_1x_2+c_0x_3 \end{bmatrix} = \begin{bmatrix} c_2x_2+c_1x_3+c_0x_0+0+0+0 \\ 0+c_2x_3+c_1x_0+c_0x_1+0+0 \\ 0+0+c_2x_0+c_1x_1+c_0x_2+0 \\ 0+0+0+c_2x_1+c_1x_2+c_0x_3 \end{bmatrix} \tag{3.8}$$

The scheme assumes that one part of the alignment signal provides circularity and another part cancels ISI into the next symbol. Thus, the ideal signal received by the receiver has the same form of equation (3.9) , which is a circular matrix in the first 4 rows and no ISI into later symbol. Equation (3.10) illustrates the form of ideal alignment signal which is supposed to appear in the receiver side, and then we calculates the form of alignment signal in the transmitter side through the equation (3.11) and (3.12).

$$y = \begin{bmatrix} c_0x_0+0+c_2x_2+c_1x_3 \\ c_1x_0+c_0x_1+0+c_2x_3 \\ c_2x_0+c_1x_1+c_0x_2+0 \\ 0+c_2x_1+c_1x_2+c_0x_3 \\ 0+0+0+0 \\ 0+0+0+0 \end{bmatrix} \tag{3.9}$$

$$y_{as} = \begin{bmatrix} 0+0+c_2x_2+c_1x_3 \\ 0+0+0+c_2x_3 \\ 0+0+0+0 \\ 0+0+0+0 \\ 0+0-c_2x_2-c_1x_3 \\ 0+0+0-c_2x_3 \end{bmatrix} \tag{3.10}$$

Equation (3.11) is the convolution function of channel and signal. Hamamreh and his team tried to reverse the convolution progress by using equation (3.12). The two approaches they provided in the article used a same method, which aims to find out the approximate inverse matrix of channel convolution matrix h.

$$y_{as} = hx_{as} \tag{3.11}$$

$$x_{as} = h^{-1}y_{as} \tag{3.12}$$

As we discussed in the previous chapter, the inverse of channel convolution matrix cannot be done accurately, and this is also mentioned in [7]. What's more, stimulations of two approaches about CP-free-OFDM are not working well with higher QAM modulation order. Thus, we suggest a novel new approach to generating the alignment signals; it is called modified CP-free-OFDM. The new approach aims to calculate the alignment signal in the frequency domain. Similar to ZP-less OFDM, the modified CP free OFDM needs to know channel information beforehand and calculate the alignment signal in the receiver side. By checking the signals which can provide circularity and cancel ISI in the equation (3.10) , we found the difference between the two signals is the sign. Thus, the modified CP-free OFDM only needs to calculate the alignment signal which can provide circularity and adds negative sign to get the the ISI canceling signal. Our scheme transfers signal and channel taps to the frequency domain by using FFT to get frequency domain signal Y_{as} and channel frequency response H. It needs to be mentioned that the FFT size used in the calculation of Y_{as} and H are the same with the FFT size of FFT block in the receiver side. Then we get X_{as} from equation (3.13), and use the IFFT process to get x_{as} in the time domain:

$$X_{as}(k) = Y_{as}(k)/H(k) \tag{3.13}$$

$$x_{as} = IFFT(X_{as}) \tag{3.14}$$

The final output of modified CP-free OFDM transmitter is:

$$x = x_{info} + x_{as} \tag{3.15}$$

4 IMPLEMENTAION

4.1 Overview

Figure 4.1 and figure 4.2 illustrate the structures of modified CP-free OFDM transmitter and receiver respectively. Unlike the aforementioned conventional CP-OFDM in chapter 2, the modified CP-free OFDM design does not have CP adding and CP dropping procedures. Instead, a well-designed alignment signal is added on the top of the OFDM symbol and it provides circularity and cancels ISI. Besides that, modified-CP OFDM calculates alignment signal in the frequency domain, thus it simplifies the procedures given by Hamamreh et al. [7]] for calculating the inverse of channel convolution matrix. Main difference of two CP-free OFDM approaches is generating an alignment signal with or without considering the next and previous symbols. However, modified CP-free OFDM can cancel ISI generated by itself and provides circularity at the same time without taking neighbor symbols into account.

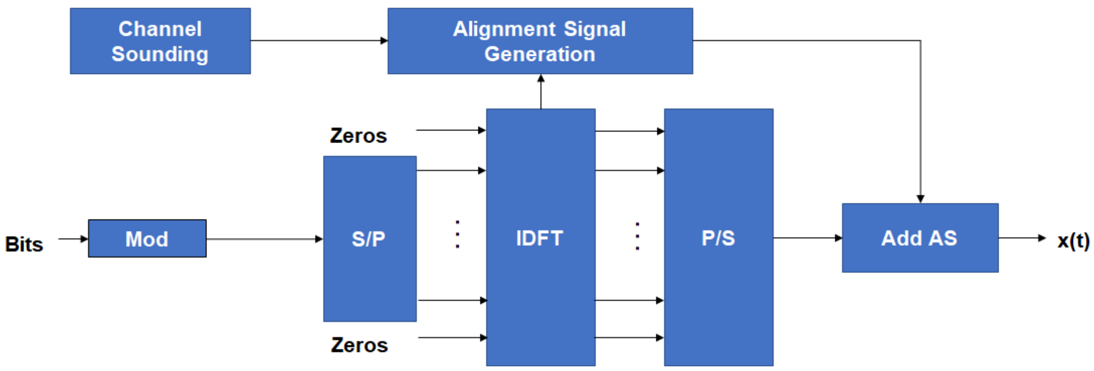


Figure 4.1. *Modified CP free OFDM transmitter structure*

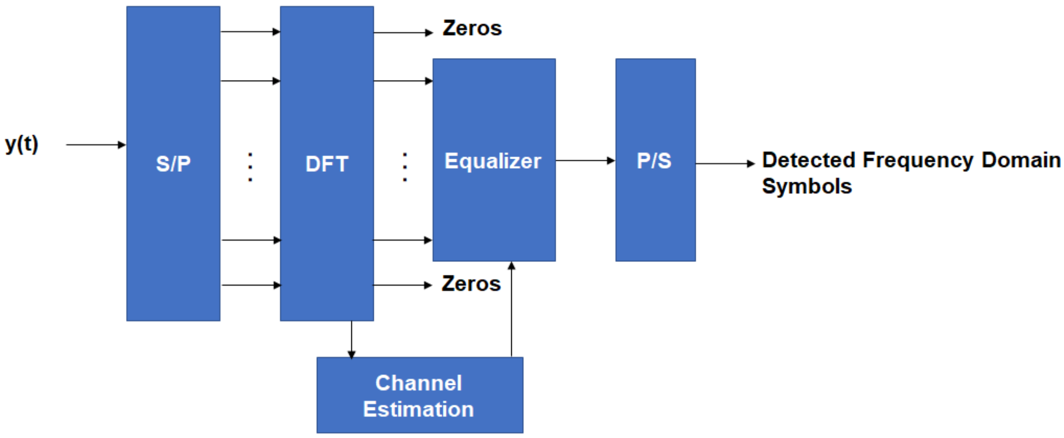


Figure 4.2. *Modified CP-free OFDM receiver structure*

4.1.1 Modified CP-free OFDM signal structure

Figure 4.3 shows the structure of a modified CP-free OFDM signal. Here the circularity providing signal, ISI canceling signal, circularity provided signal and ISI canceling signal are marked by the color yellow, blue, green and red, respectively. In the ideal case, circularity providing signal will locate at the beginning of the original symbol where it calculated from; ISI canceling signal can automatically cancel the ISI into later symbols.

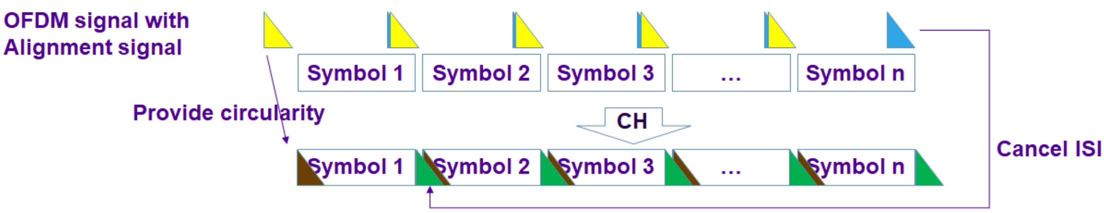


Figure 4.3. *Modified CP-free OFDM signal structure of one slot*

In this design, the alignment signal is added on the top of the OFDM symbols without changing the symbol length. However, the alignment signal is arranged at the end of previous symbol to providing ISI canceling and circularity providing functions to current symbols. As figure 4.3 shows, the alignment signal of symbols 2 is arranged at the end of symbol 1. Thus, the alignment of symbol 1 should be arranged before the symbols to proving circularity, and this would extend the length of the first symbol. For unifying the length of symbols, in our design, symbol 1 and 2 are training symbols containing the same information. Then symbol 1 can be seen as a long CP for symbol 2, which can then be used for channel estimation in the conventional way. In that case, the function of training symbol is kept without adding alignment signal for symbol 1 and all symbol lengths are equal.

4.2 Channel estimation and noise

Wireless channel has tremendous varieties which lead to phase distortion, amplitude distortion, and frequency offset. All those problems bring challenges for signal recovering. Also, good channel estimation is an essential part of channel equalization, best matching receiver detection, coherent demodulation, as well as for link adaptation. Thus, channel estimation is an important part of wireless communication. Channel estimation can be divided into two approaches, one is based on training symbols, another one is based on blind channel estimation. The first approach sends pilot signals regularly. Pilot symbols can be inserted as known subcarrier symbols scattered among the date symbols according to some specific pattern. Alternatively, training symbol can be adapted for various wireless communication systems scenarios, but they lower the power efficiency and spectrum efficiency. Besides that, the receiver spends time to get the whole training symbol for the later equalization, that will lead to unavoidable delay. On the contrary, blind channel estimation does not need a training symbol as it utilizes information data to estimate the channel. Apparently, Blind channel estimation improves the spectrum efficiency, but it needs complex algorithms and has less flexibility, so it has many limitations in practical applications. Channel estimation is an essential part of alignment signal generation. While leaving the suitable channel estimation specifics for modified CP-free OFDM as a topic for future work, we utilize a basic channel estimation procedure in order to obtain realistic link performance results through simulations. Channel estimation is done in FFT-domain, since alignment signal is generated in frequency domain. It is based on a single training symbol using the CP-OFDM signal structure, and the channel is assumed to be constant over the transmission frame.

During the simulations, additive white Gaussian noise (AWGN) is added to the received signal. AWGN noise has two characteristics. First, it fulfills the standard of white noise which has a constant power spectral density, [38][39] and the definition can be derived in equation 4.1:

$$P_n(f) = \frac{n_0}{2} for(-\infty < f < +\infty) \tag{4.1}$$

Second, the probability density function of AWGN is the normal distribution. Normal distribution or Gaussian distribution is denoted as N (μ, σ^2) where μ is the expectation and σ^2 is variance [40][38], and it can be expressed as:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} exp(-\frac{(x-\mu)^2}{2\sigma^2}) \tag{4.2}$$

AWGN reflects the noise situation in the actual communication channel, it has similar characteristics with the real channel noise, and it can be expressed by specific mathematical expressions which are easier for analyzing and calculating. Thus, AWGN is widely used in the theoretical analysis of communication systems.

4.3 Channel models

Channel plays an important role in all the simulations we have done for modified CP-free OFDM and conventional CP-OFDM since it not only influences the link performance of information signal but also generates problems for channel sounding. Thus, the more practical the channel models are used in the simulations the more reliable our simulation results will be. Channel models can be classified into two types, non–line of sight (NLOS) and line of sight (LOS). What's more, based on the 5G and LTE report from 3GPP about frequency spectrum above 6 GHz, we selected tapped delay line (TDL) channel models TDL-C and TDL-D from the total five-channel models given by the report as our channel models to test the performance of modified CP-free OFDM. TDL-C channel represents a NLOS profile and TDL-D channel models a LOS channel.

The RMS delay spread values of these two TDL models are normalized and they can be scaled in delay so that a desired RMS delay spread can be achieved. The scaled delays is given as a parameter to the models.

5 RESULTS AND ANALYSIS

This chapter will analyze the performance of modified CP-free OFDM with the reference of conventional CP-OFDM. The analysis of results will start from the comparison of ZP-less OFDM and modified CP-free OFDM to prove the performance enhancement introduced by the modified CP-free OFDM design provided in this thesis. The later comparisons are focused on modified CP-free OFDM in two different transmission environments: (i) NLOS environment using the TDL-C channel model and (ii) LOS environment using the TDL-D channel model. In both cases, the basic scheme and another scheme with channel pre-equalization on the transmitter side are evaluated. Also, each subsection in the below comparison categories contains figures of BER performance, CP length influence, PSD (power spectrum density) and PAPR (complementary cumulative distribution function) of PAPR. In pre-equalization cases, no channel equalization is applied on the receiver side. In all other cases, conventional OFDM channel equalization is applied on the receiver side and it is based training symbols with power level equal to the data symbols. Channel knowledge is an important part of alignment signal generation; all channel information is obtained by channel estimation under the same conditions as data transmission. The channel estimate for each subcarrier is obtained from a single BPSK modulated pilot symbol, the symbol energy and numbers of active subcarriers will be given in each subsection. It is important to notice that also channel knowledge outside the active data subcarriers is useful and helps to enhance the performance of the CP-less schemes.

5.1 ZP-less OFDM vs. modified CP-free OFDM

The main idea of this section is to show the performance of ZP-less [7] and modified CP-free OFDM with the reference of CP-OFDM while CP length equals to 18 and 0. As Hamamreh and his team's publication [7] described, the channel information is assumed perfectly known by the receiver before generating an alignment signal. Thus, we start those simulations with the parameters shown in the table 5.1, and assume the channel information is fully known by the receiver.

Table 5.1. *Parameters of ZP-less OFDM vs. modified CP-free OFDM*

Modulation Type	Modified CP-free OFDM & ZP-less OFDM
Channel Model	A) Rayleigh multipath time dispersive channel[7], zero mobility, Decaying factor=1,2,3 B) TDL-C, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	16
CP length	18, 0
Alignment signal length	18 (modified CP-free OFDM)
Channel knowledge in AS generation	Ideal channel knowledge
Active subcarriers / FFT size	256/256

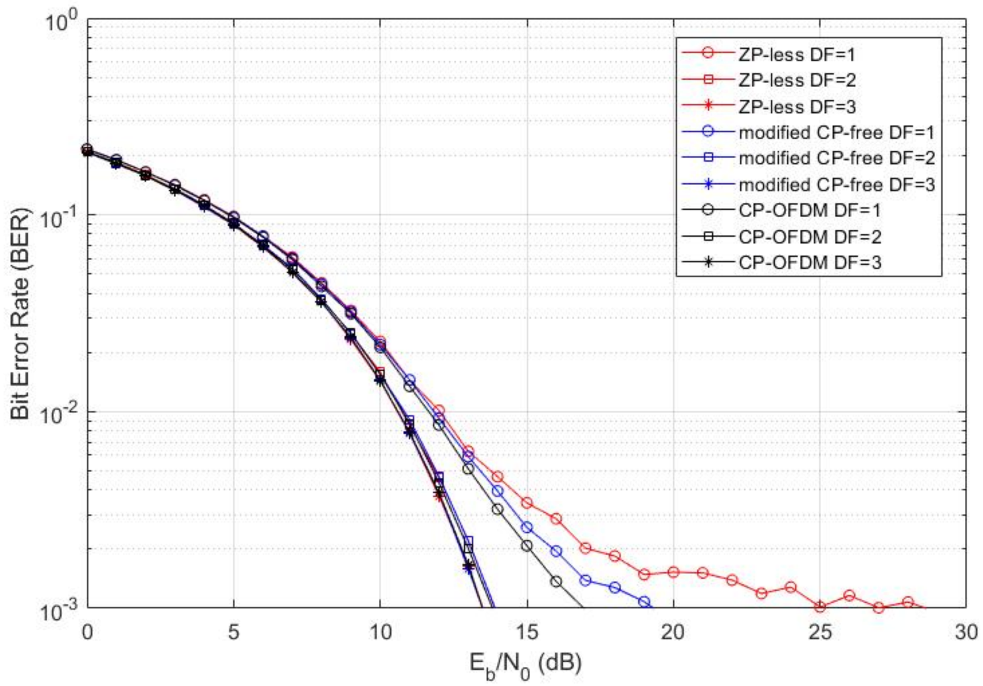


Figure 5.1. *BER performance of ZP-less OFDM, modified CP-free OFDM and 18-CP-OFDM with the channel of [7].*

Simulations start with the Rayleigh channel used in [7]. The BER performance comparison between ZP-less OFDM, modified CP-free OFDM and conventional CP-OFDM is shown in 5.1. The delay factor is a parameter used to control the delay profile of the channel and high delay factor means short ISI would be generated by multi path propagation. The modified CP-free OFDM provides similar performance with other two approaches while delay factor equals to 2 and 3, and also close to other two approaches performance with 1 delay factor.

Next, the Rayleigh channel model is replaced by a more practical channel model (TDL-C) to analyse the performance of modified CP-free OFDM and ZP-less OFDM. Comparing figures 5.2 and 5.3, they clearly show the ZP-less method is able to reduce the BER without using CP in all three-channel models with different delay profiles. However, the modified CP-free OFDM can provide significantly better performance compared with ZP-less. Thus, the following comparisons will focus on the performance of the modified CP-free OFDM with different transmission schemes and channels to explore the limits of the new design provided in this thesis.

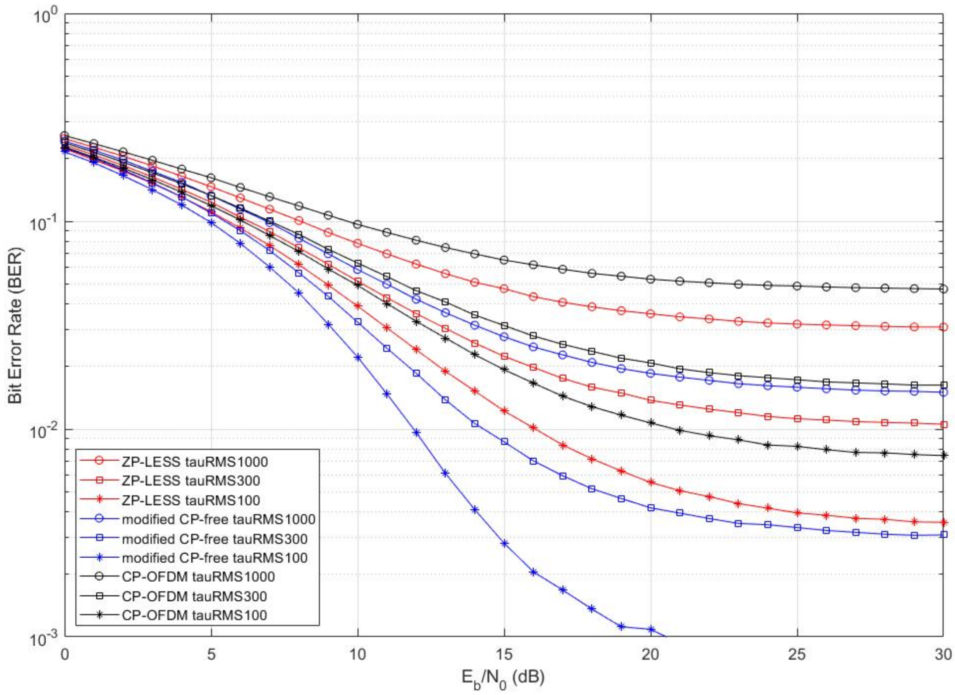


Figure 5.2. *BER performance of ZP-less OFDM, modified CP-free OFDM and 0-CP-OFDM with the channel of TDL-C.*

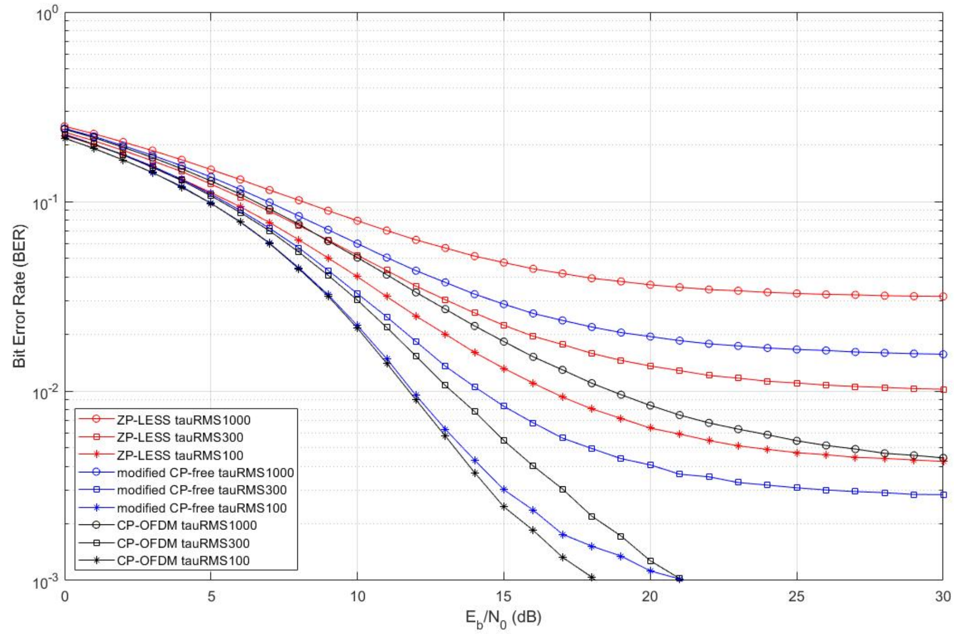


Figure 5.3. *BER performance of ZP-less OFDM, modified CP-free OFDM and 18-CP-OFDM with the channel of TDL-C.*

5.1.1 Performance with NLOS communication channel

a) Ideal channel knowledge

Table 5.2. *Parameters in ideal channel knowledge case*

Modulation Type	Modified CP-free OFDM & CP-OFDM
Channel Model	TDL-C, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	64
CP length	18, 0
Alignment signal length	18
Channel knowledge in AS generation	Ideal channel knowledge
Active subcarriers / FFT size	256/256

The analyses of modified CP-free OFDM in this section start still from the ideal case, in which the transmitter already knows the exact channel information before sending the OFDM signal. Thus, we explore how good the performance of modified CP-free OFDM would be in the ideal channel knowledge situation.

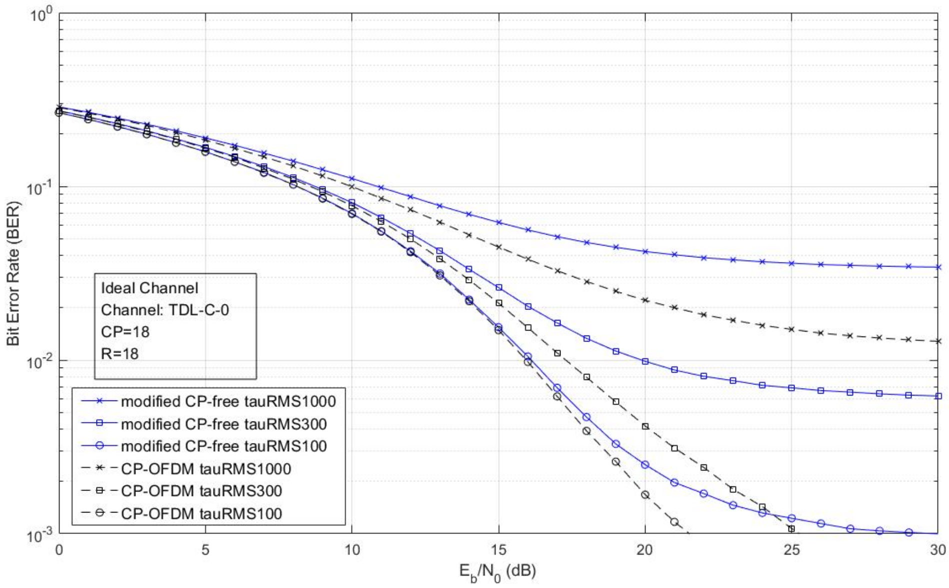


Figure 5.4. *BER Performance of modified CP-free OFDM and CP-OFDM with ideal TDL-C channel knowledge.*

For proving the benefit of modified CP-free OFDM, the figure 5.5 shows the performance of CP-OFDM while CP=0. These figures show that the modified CP-free OFDM has significant performance improvement when not using CP, meanwhile the BER performance of modified CP-free OFDM is very close to normal CP-OFDM in the low root mean squared (RMS) delay spread situation. Figure 5.6 shows the CCDF of PAPR for modified CP-free and CP-OFDM. Since the channel delay profile influences the alignment signal, the PAPR plots with the three delay profile are illustrated in that figure including CP-OFDM as reference. Although the channel delay profile can influence the PAPR of modified CP-free OFDM, the maximum PAPR difference between CP-OFDM and modified CP-free OFDM is less than 0.4 dB.

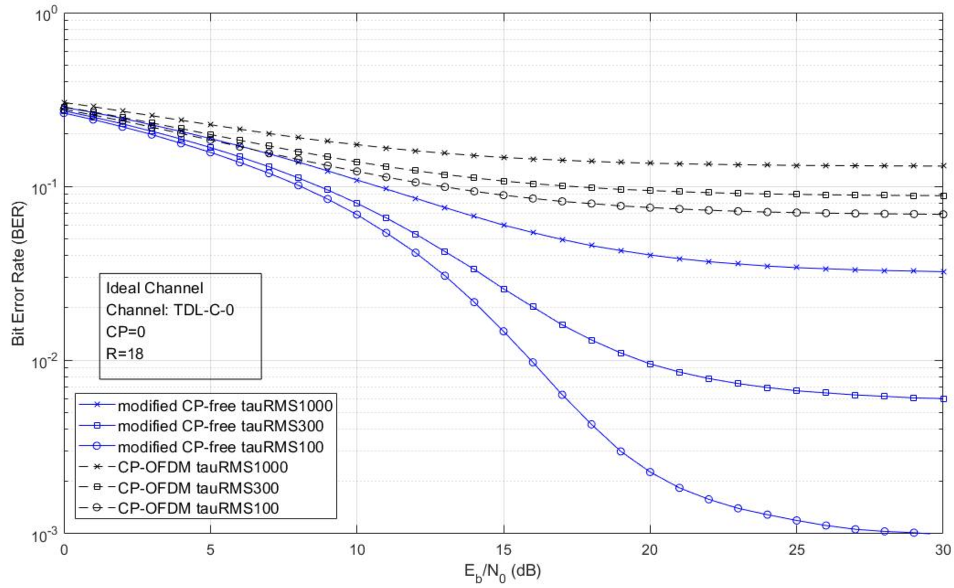


Figure 5.5. *BER performance of modified CP-free OFDM and 0-CP-OFDM with ideal TDL-C channel knowledge.*

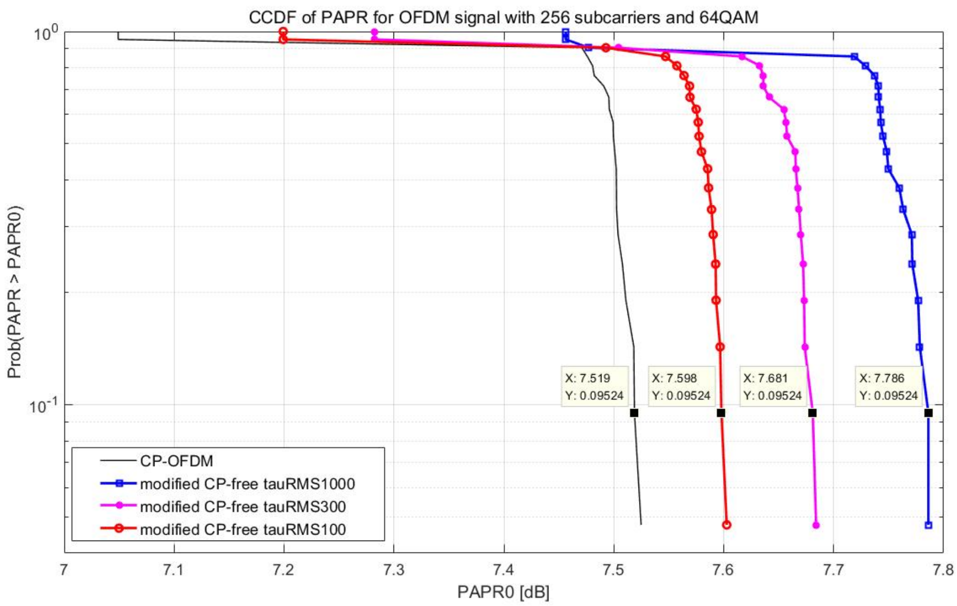
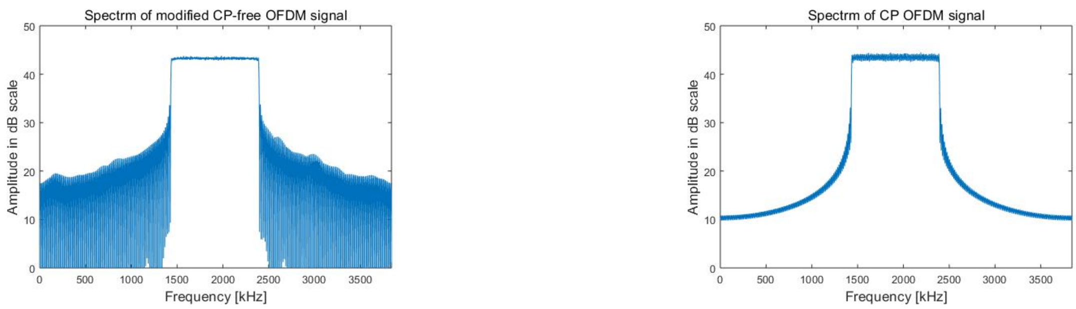


Figure 5.6. *PAPR of modified CP-free OFDM and CP-OFDM with ideal TDL-C channel knowledge.*

Figure 5.7 illustrates the power spectrum density of modified CP-free OFDM and CP-OFDM signal before and after passing the channel. The spectrum of modified CP-free OFDM has stronger out of band emission compared with CP-OFDM and that will lead to increased interference leakage to adjacent channels.



(a) ***(b)***

Figure 5.7. *Spectrum comparison of modified CP-free OFDM (a) and CP-OFDM (b) with ideal TDL-C channel knowledge.*

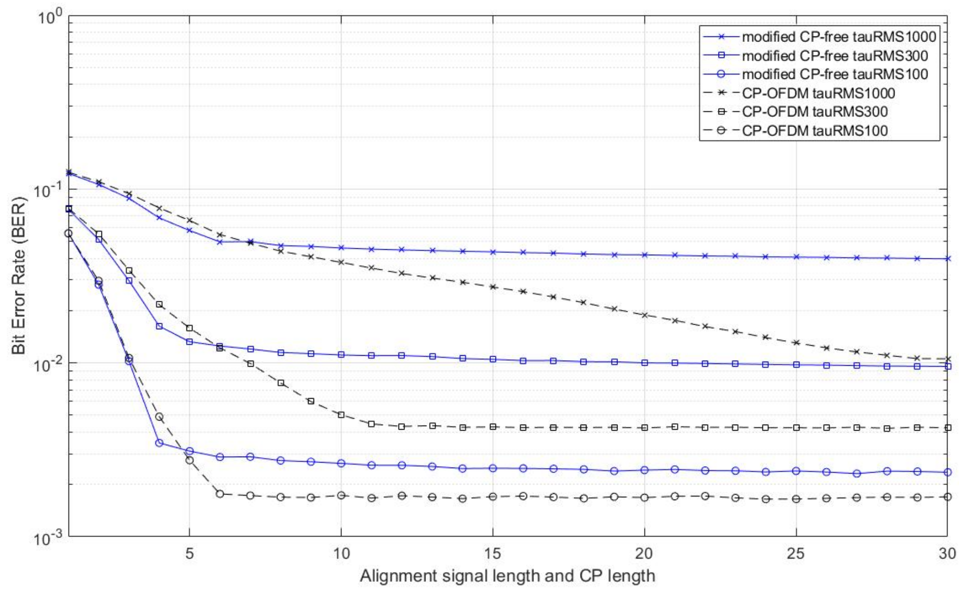


Figure 5.8. *Alignment signal length and CP length influence of modified CP-free OFDM and CP-OFDM with ideal TDL-C channel knowledge and Eb/No = 20 dB.*

CP is the key element to grantee that whether the signal can be recovered correctly and its ability is heavily depending on the length of CP in relation to the maximum delay spread. As we talked in the previous chapter, the longer CP, the stronger ability against multipath channel effects CP-OFDM has. With the 1000 ns delay channel, the BER curve is clearly going down with the increasing of CP length. However, modified CP-free OFDM performance reaches the minimum BER level quickly with increasing alignment signal length. Thus we select 18 as the length of the alignment signal to make sure that the BER performance of modified CP-free OFDM is not compromised. In that case, the modified CP-free OFDM has sufficient aliment signal length for the considered delay profiles. Besides that, the alignment signal length in [7] is equal to the symbol length, and it would be 256 samples in our simulation scenarios. Thus, this figure clearly shows that the CP-free approach provided in this thesis reduces the alignment signal length significantly.

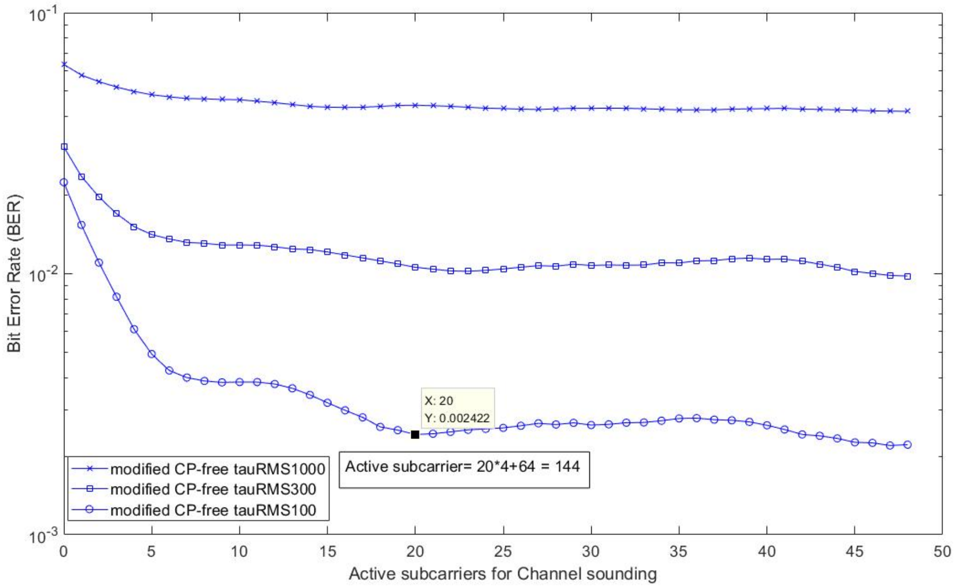


Figure 5.9. *The influence of channel knowledge bandwidth on the BER performance of modified CP-free OFDM and Eb/No = 20 dB.*

So far we have assumed that channel knowledge is available for all subcarriers corresponding to the FFT size. However, practical implementations require guard bands to reduce the interference to adjacent frequency channels. Therefore, we plot the figure 5.9 to show the influence of BER performance while we decrease the channel knowledge bandwidth. From the figure, we can see that the BER performance is close to full band channel knowledge case in low delay profile when active subcarrier number reaches to 144. If the channel knowledge is limited to active subcarrier bandwidth, the performance of CP-less schemes is severely affected.

It needs to be mentioned that the pilot symbols for channel estimation are usually available only within the bandwidth of the active data subcarriers. Using channel reciprocity, the uplink channel knowledge can be estimated from the downlink pilots in TDD systems. Then wider channel knowledge bandwidth is feasible especially in the uplink of TDD systems.

b) Full band channel estimation

This section reports simulation results for modified CP-free OFDM and CP-OFDM while channel estimation is working in a practical situation which has noise involved in the channel estimation procedure. Figure 5.10 illustrates the BER performance of Modified CP-free and CP-OFDM under this more practical situation. Compared with the figure 5.4 of the ideal case, modified CP-free OFDM has worse performance, since alignment signal generation is based on noisy channel estimate.

Table 5.3. *Parameters in full band channel estimation cases*

Modulation Type	Modified CP-free OFDM & CP-OFDM
Channel Model	TDL-C, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	64
CP length	18
Alignment signal length	18
Channel knowledge in AS generation	Training symbol based
Active subcarriers / FFT size	256/256

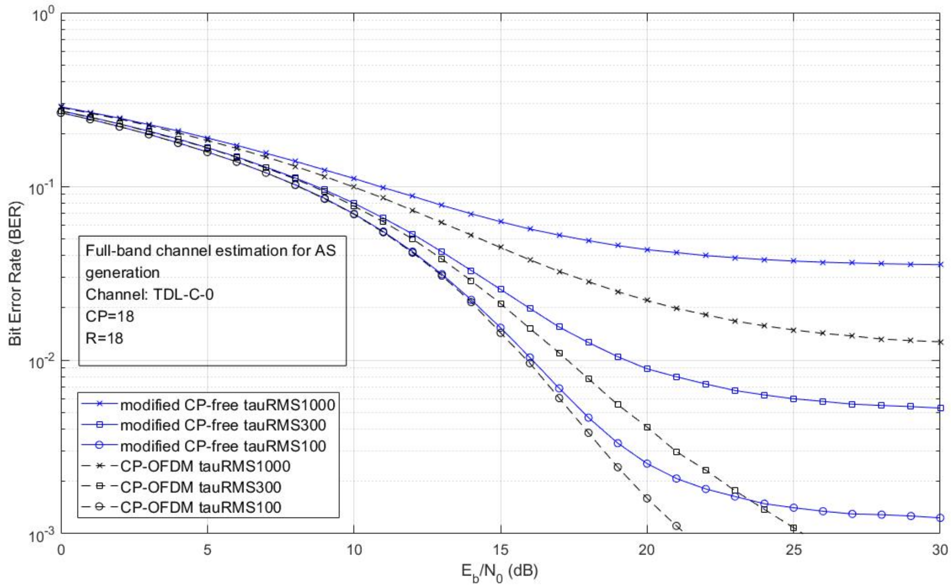


Figure 5.10. *BER performance with modified CP-free and CP-OFDM with full band channel estimation.*

The CCDF of PAPR still follows the results of the ideal case,i.e., higher channel delay would introduces higher PAPR. However, the maximum PAPR difference between two methods still less than 0.4 dB even with noise influence in channel estimation.

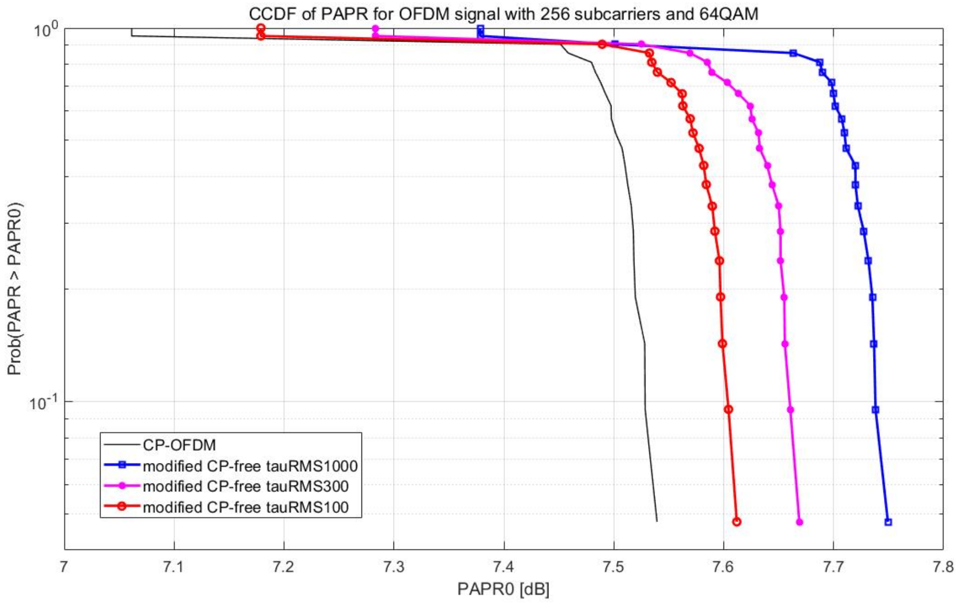
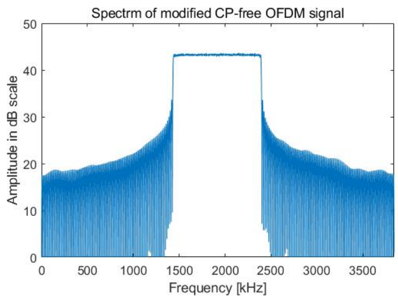
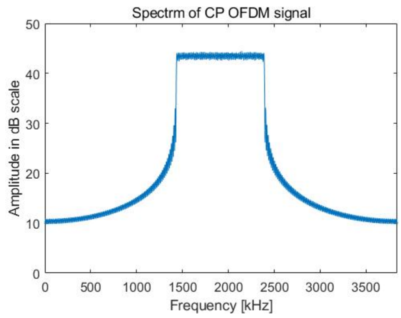


Figure 5.11. *PAPR of modified CP-free and CP-OFDM full band channel estimation.*



(a)



(b)

Figure 5.12. *Spectrum comparison of modified CP-free OFDM (a) and CP-OFDM (b) with fullband TDL-C channel knowledge.*

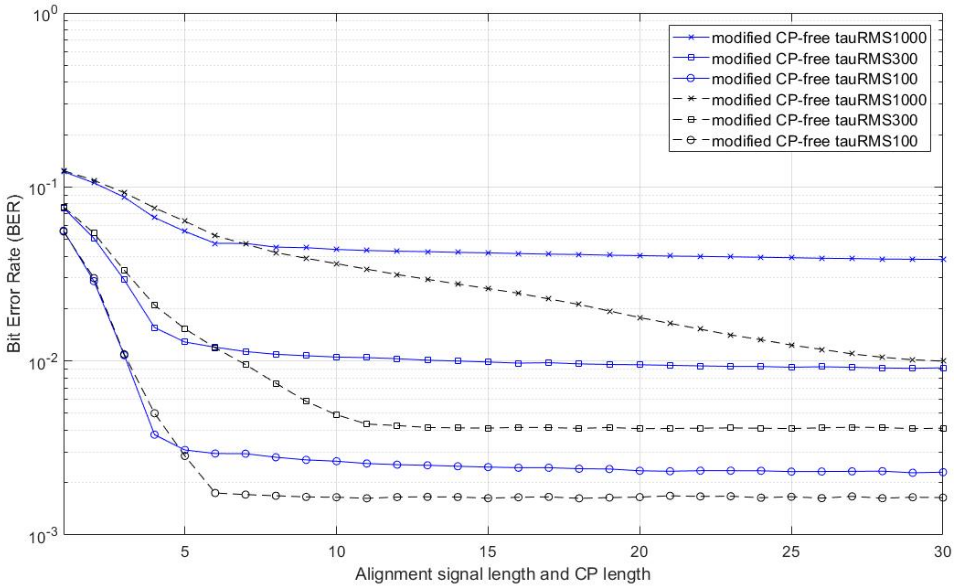


Figure 5.13. *Alignment signal length and CP length influence of modified CP-free OFDM and CP-OFDM with fullband TDL-C channel knowledge and Eb/No = 20 dB.*

The above figure 5.13 shows that modified CP-free OFDM can reach the lowest BER performance with short alignment signal length and which is not influenced by the noise of channel estimation. The spectrum in figure 5.12 point out that the OOBE phenomenon is still stronger than in conventional CP-OFDM.

c) Pilot Boosting Channel Estimation

Table 5.4. *Parameters in pilot boosting channel estimation case*

Modulation Type	Modified CP-free OFDM & CP-OFDM
Channel Model	TDL-C, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	64
CP length	18
Alignment signal length	18
Channel knowledge in AS generation	Training symbol based
Active subcarriers / FFT size	256/256

Continuing from the previous comparison, pilot signal enhancement is deployed in channel estimation using 3 dB stronger power than the info signal transmitted in the system. This pilot boost is applied only in the alignment signal generation. Results are shown in 5.14-5.17. Notably, the BER performance is improved as expected.

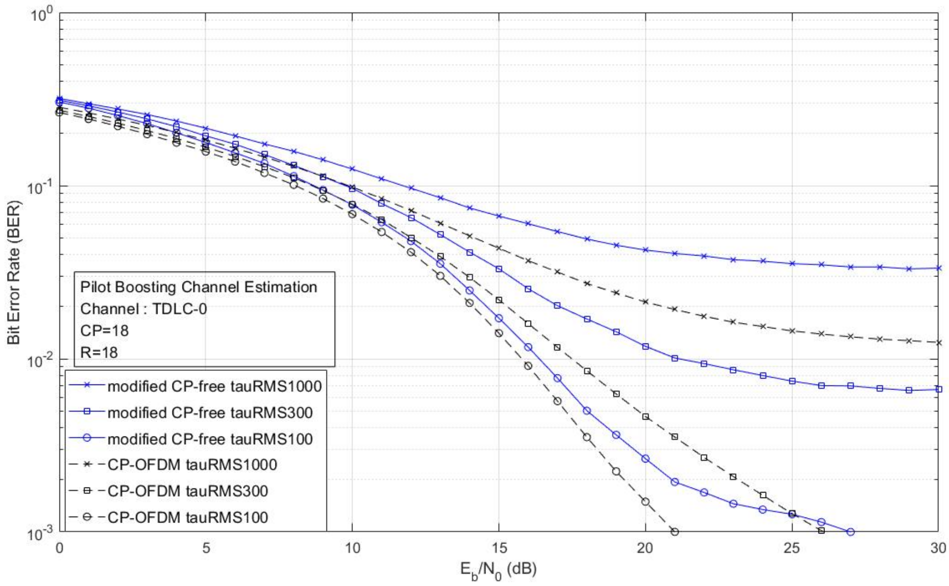


Figure 5.14. *BER Performance of modified CP-free and CP-OFDM with pilot boosting TDL-C channel estimation.*

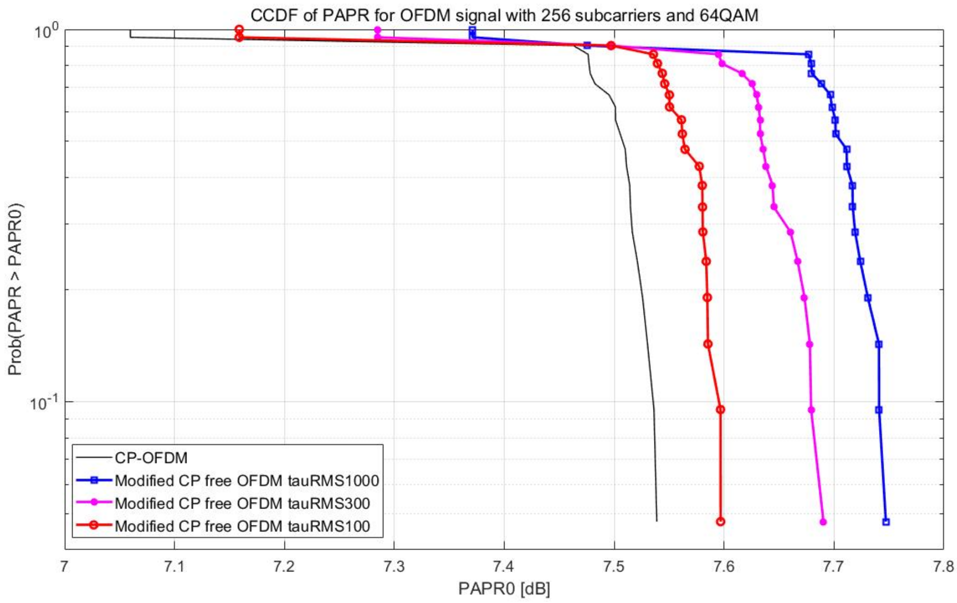
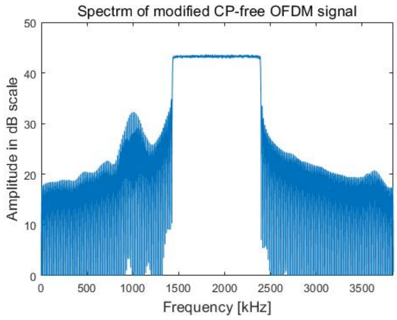
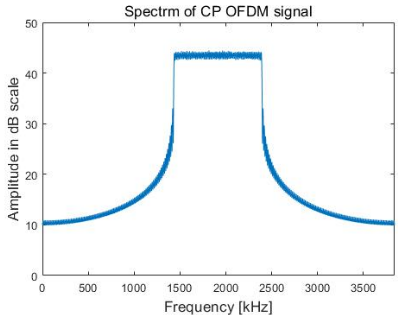


Figure 5.15. *PAPR of modified CP-free and CP-OFDM with pilot boosting TDL-C channel estimation.*



(a)



(b)

Figure 5.16. *Spectrum comparison of modified CP-free OFDM (a) and CP-OFDM (b) with pilot boosting TDL-C channel estimation.*

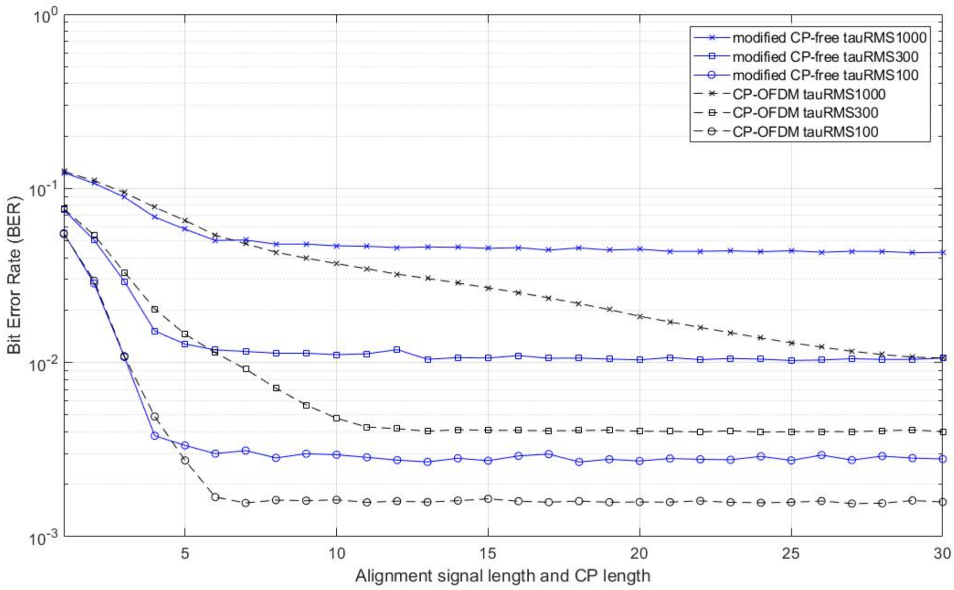


Figure 5.17. *Alignment signal length and CP length influence of modified CP-free OFDM and CP-OFDM with pilot boosting TDL-C channel estimation and Eb/No = 20 dB.*

d) Pre-equalized scheme with ideal channel knowledge

This section will explore the performance of modified CP-free OFDM, including comparison with CP-OFDM under the pre-equalization scheme. 64 QAM is adapted firstly in the below simulations. Figure 5.18 and 5.19 show the performance of pre-equalized modified CP-free which is significantly better than the pre-equalized CP-OFDM with zero CP-length. However, pre-equalization doesn't bring performance improvement to modified CP-free OFDM as it brings to CP-OFDM; CP-OFDM works better with the helping of pre-equalization especially in the 100 ns and 300 ns delay profile cases. However, with zero CP-length the CP-OFDM performance degrades severely.

__Table 5.5.__ Parameters in pre-equalized cases with ideal channel knowledge.

Modulation Type	Pre-equalized modified CP-free OFDM Pre-equalized CP-OFDM
Channel Model	TDL-C, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	16,64
CP length	18,0
Alignment signal length	18
Channel knowledge in AS generation	Ideal channel knowledge
Active subcarriers / FFT size	256/256

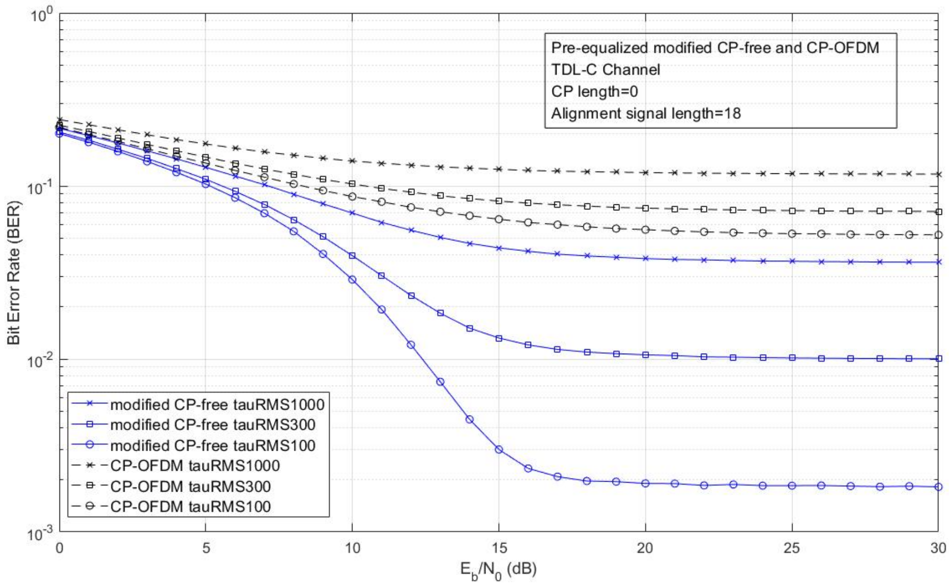


Figure 5.18. *BER performance of pre-equalized modified CP-free OFDM and pre-equalized 0-CP-OFDM.*

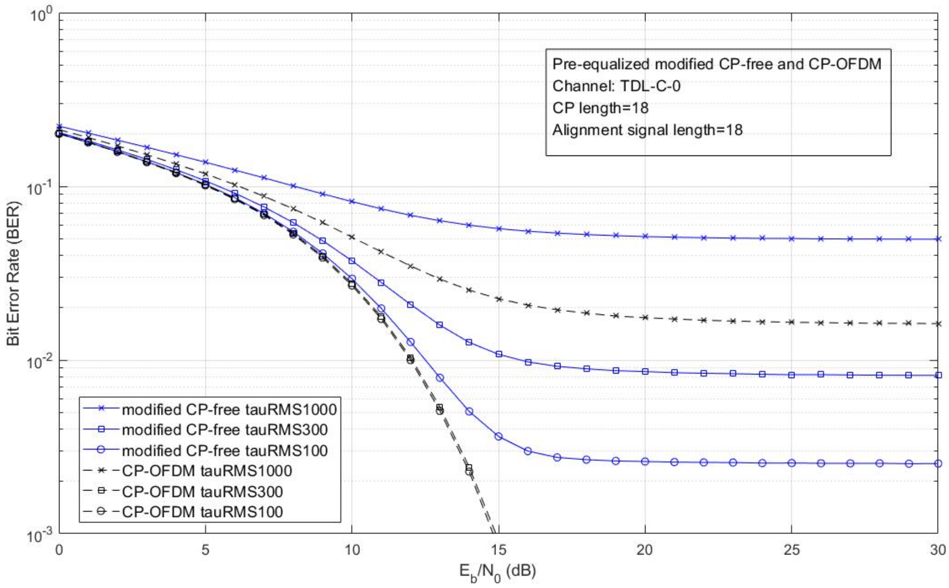


Figure 5.19. *BER performance of pre-equalized modified CP-free and pre-equalized 18-CP-OFDM.*

The maximum difference of PAPR between pre-equalized modified CP-free and pre-equalized CP-OFDM is around 0.45 dB.

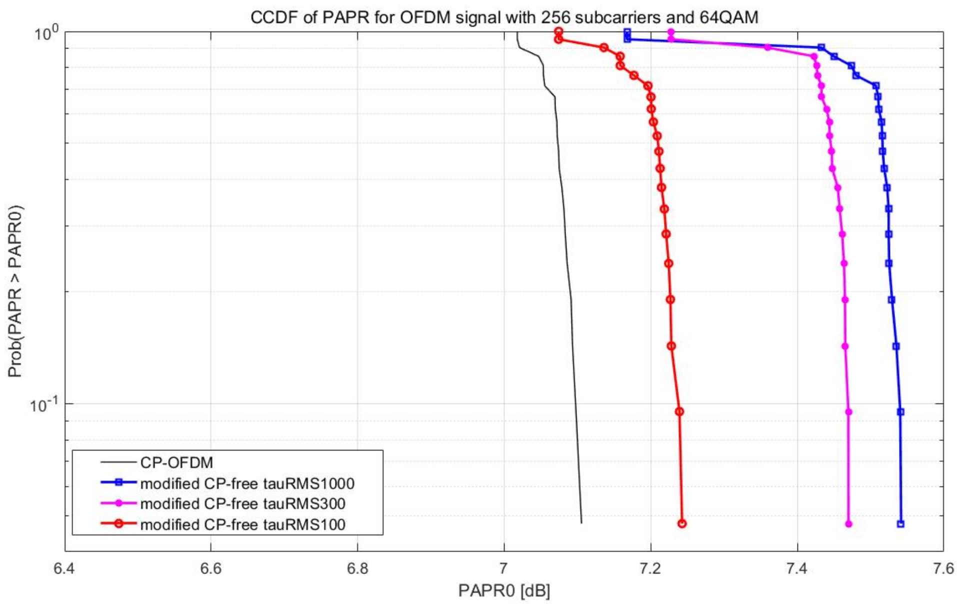


Figure 5.20. *PAPR of pre-equalized modified CP-free and pre-equalized CP-OFDM with ideal TDL-C channel.*

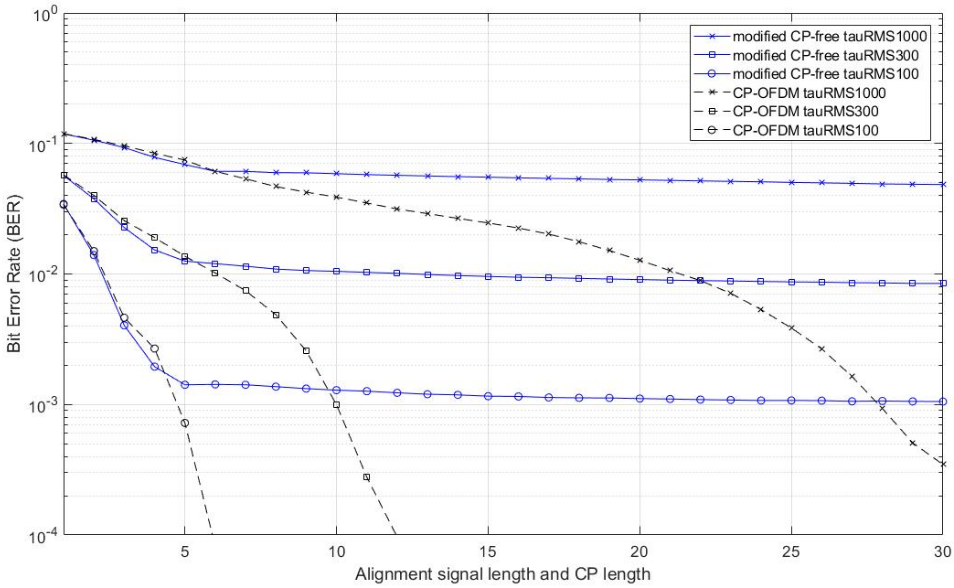


Figure 5.21. *Alignment signal length and CP length influence of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with ideal TDL-C channel knowledge and Eb/No = 20 dB.*

Comparing figures 5.21 and figure 5.8, pre-equalized CP-OFDM has better performance than conventional CP-OFDM in ideal channel estimation case. Also, the pre-equalization also bring a bit performance enhancement to modified CP-free OFDM. Then we decrease the modulation order from 64 to 16 to check the performance of modified CP-free OFDM with TDL-C channel. modified CP-free OFDM can provide excellent BER performance with 100 ns and 300 ns delay profile, acceptable performance for 1000 ns delay profile.

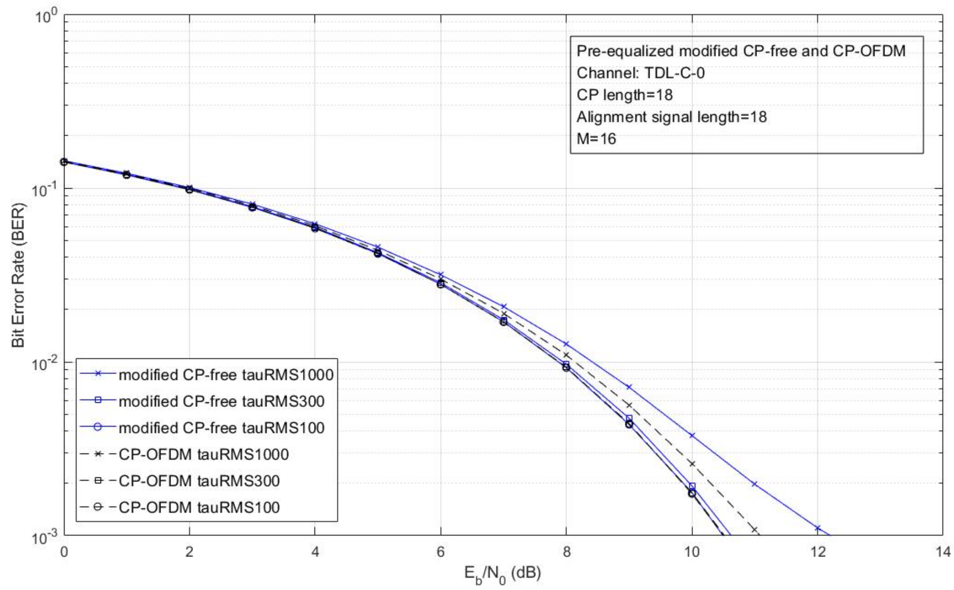


Figure 5.22. *BER performance of pre-equalized modified CP free and pre-equalized 18-CP-OFDM,16-QAM modulation.*

Active subcarrier number influence is also evaluated in this case. As shown in figure 5.23.

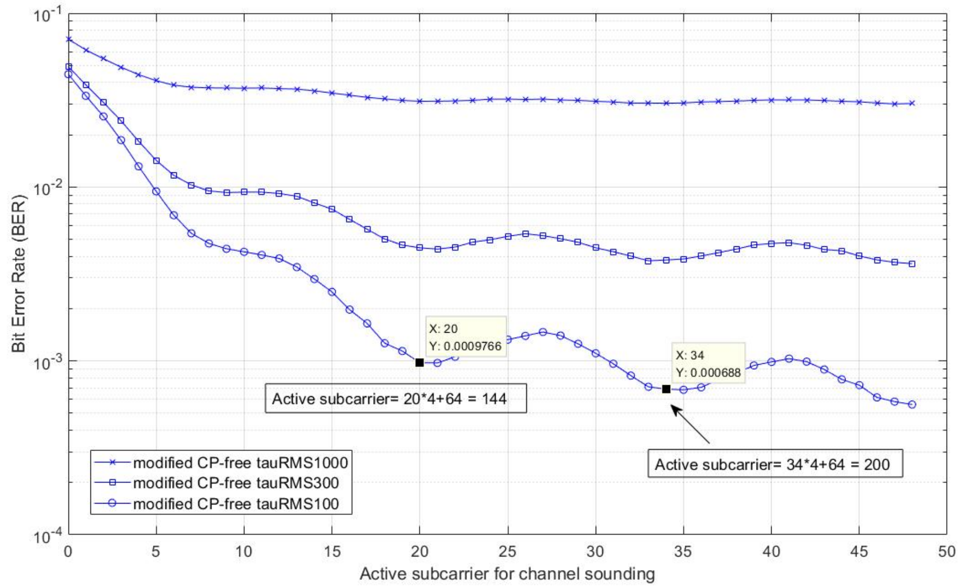


Figure 5.23. *Channel estimation active subcarrier number influence of BER performance, pre-equalization scheme with ideal channel knowledge, 64-QAM modulation and Eb/No = 20 dB.*

e) Pre-equalized scheme with pilot boosting channel estimation

Table 5.6. *Parameters in pre-equalized cases with pilot boosting channel estimation*

Modulation Type	Pre-equalized modified CP-free OFDM Pre-equalized CP-OFDM
Channel Model	TDL-C, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	64
CP length	18
Alignment signal length	18
Channel knowledge in AS generation	Training symbol based
Active subcarriers / FFT size	256/256

For the practical simulation of the pre-equalization scheme, the pilot boosting scheme is applied directly as the performance of practical pre-equalized modified CP-free is not decent and pilot boosting can provide performance improvement somehow.

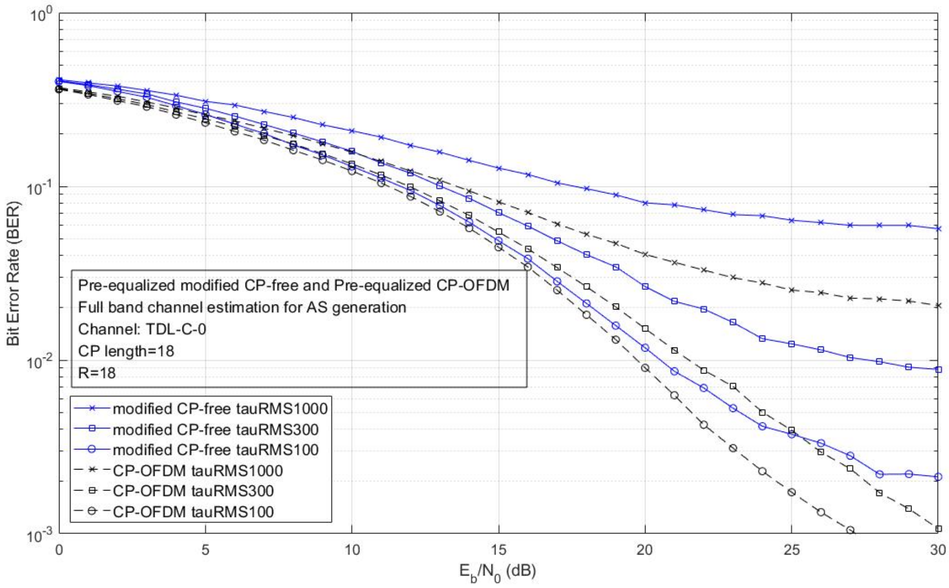


Figure 5.24. *BER performance of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with pilot boosting TDL-C channel estimation*

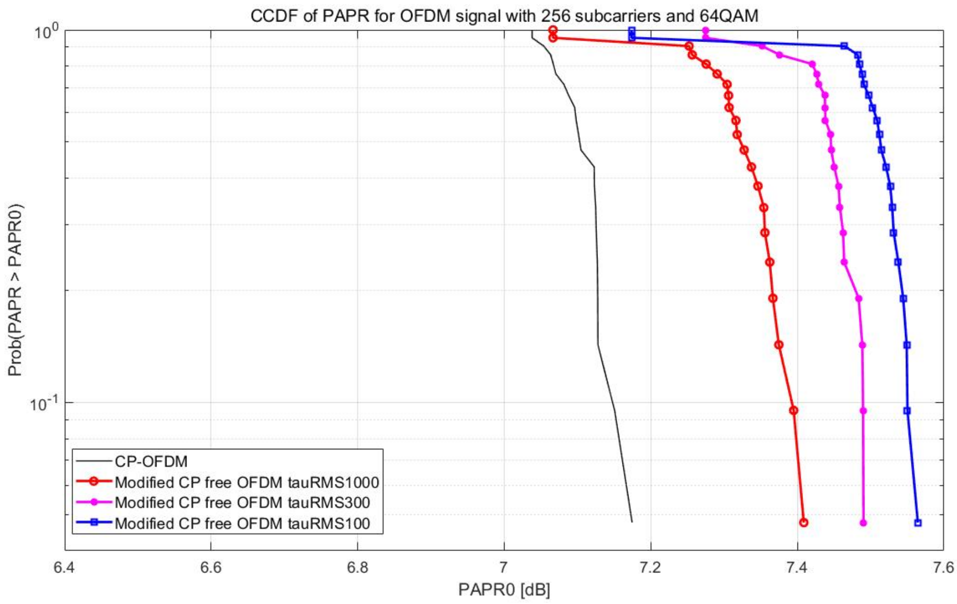
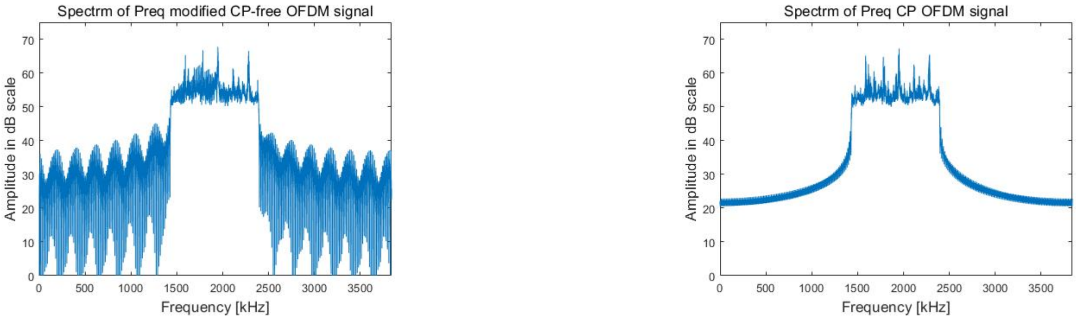


Figure 5.25. *PAPR of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with pilot boosting TDL-C channel estimation.*



(a) ***(b)***

Figure 5.26. *Spectrum comparison of modified CP-free OFDM (a) and CP-OFDM (b)with pilot boosting TDL-C channel estimation.*

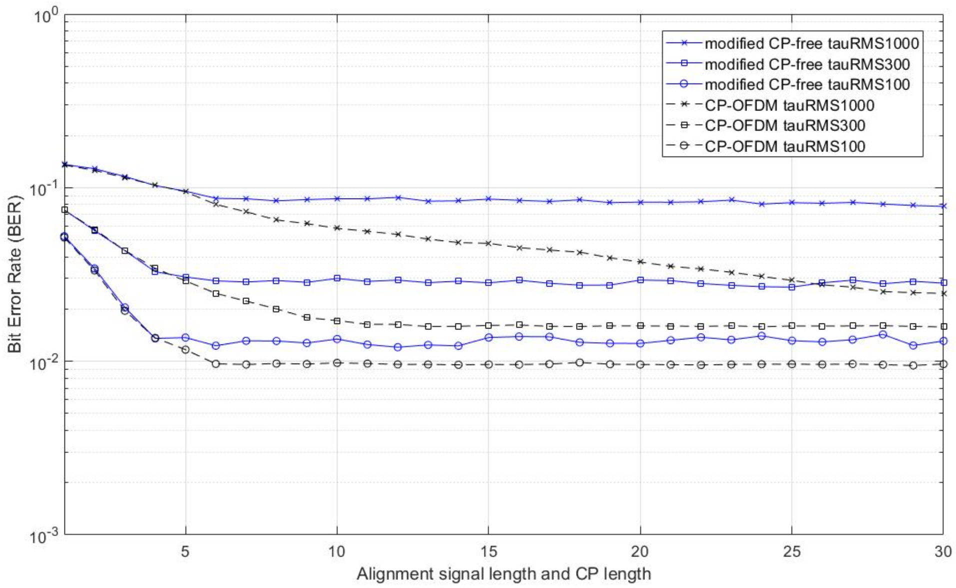


Figure 5.27. *CP and alignment signal influence of pre-equalized modified CP-free and pre-equalized CP-OFDM with pilot boosting TDL-C channel estimation and Eb/No = 20 dB.*

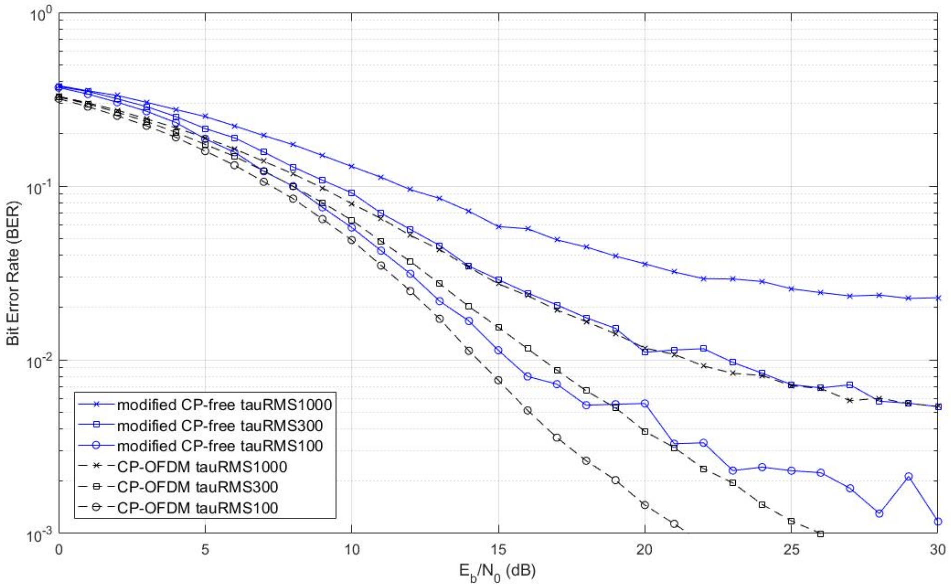


Figure 5.28. *BER performance of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with pilot boosting TDL-C channel estimation, 16-QAM modulation.*

When the modulation order reduces to 16, the performance of modified CP-free OFDM in the 100 ns delay case becomes acceptable. However, Pre-equalized CP-OFDM works well in all three cases.

5.1.2 Performance with LOS communication channel

In this section, all simulations are repeated with the TDL-C channel model. Since the previous comparisons have illustrated that modified CP-free OFDM can provide excellent performance without using CP, we will further explore how good performance we will have in TDL-D channel model with higher modulation order.

a) Ideal Channel knowledge

Table 5.7. *Parameters in ideal channel knowledge case*

Modulation Type	Modified CP-free OFDM & CP-OFDM
Channel Model	TDL-D, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	256
CP length	18
Alignment signal length	18
Channel knowledge in AS generation	Ideal channel knowledge
Active subcarriers / FFT size	256/256

This section gives the performance of modified CP-free OFDM with LOS channel model.

Figure 5.29 shows the BER performance with TDL-D channel and ideal channel knowledge in the alignment signal generation. Here the configuration is the same as in figure 5.4, except for the channel model. Comparing the values and curves in the two figures, modified CP-free OFDM has significantly better performance in the LOS situation and the three BER performance curves are close to the CP-OFDM performance curve .

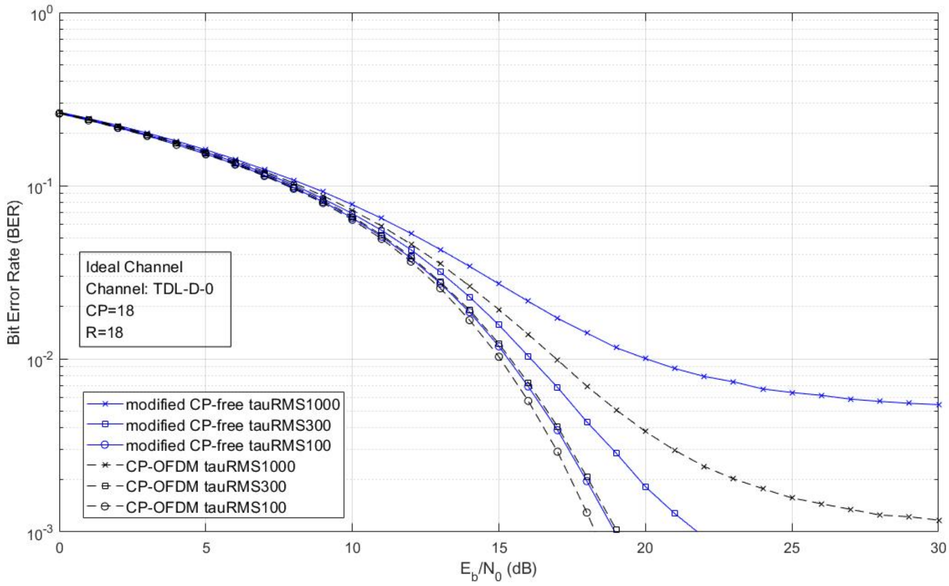


Figure 5.29. *BER Performance of modified CP-free OFDM and CP-OFDM with ideal TDL-D channel knowledge and 64-QAM modulation.*

Next we increase the modulation order from 64 to 256 to explore the performanc limitss. Figure 5.30 illustrates that modified CP-free OFDM can bring acceptable performance with the low delay channel but the other two cases have significantly reduced worse performance.

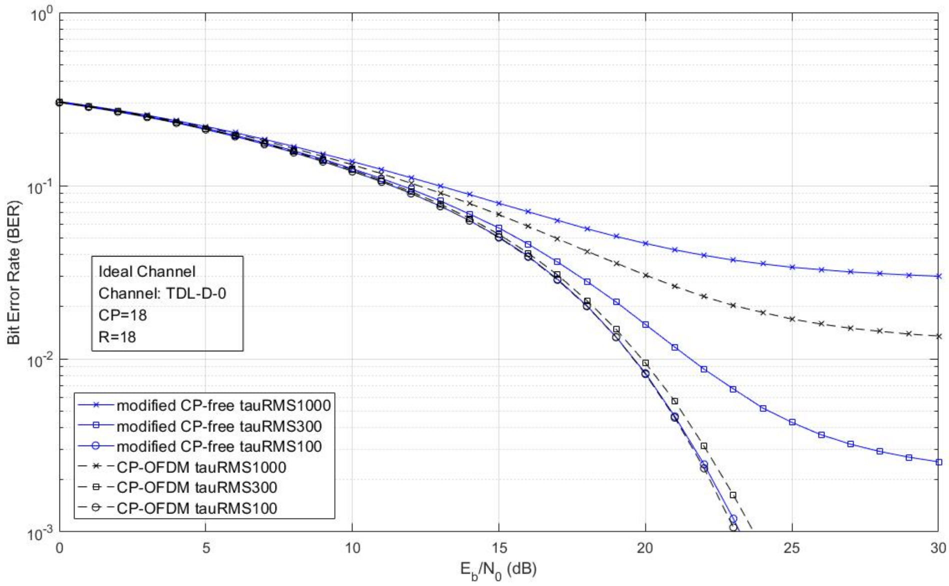


Figure 5.30. *BER Performance of modified CP-free OFDM and CP-OFDM with ideal TDL-D channel knowledge and 256-QAM modulation.*

The PAPR results of figure 5.30 are quite different from the NLOS case. The PAPR with the three different delay profiles are the same and no more than 0.05 dB from the PAPR of CP-OFDM. Figures 5.31-5.34 below illustrate the PSDs of the transmitted signals, alignment signal length influence, and channel knowledge bandwidth influence, respectively, for TDL-D channel and 256-QAM modulation assuming ideal channel knowledge in the alignment signal generation. Furthermore, figures 5.35-5.37 show the corresponding simulation results with practical channel estimation in the alignment signal generation.

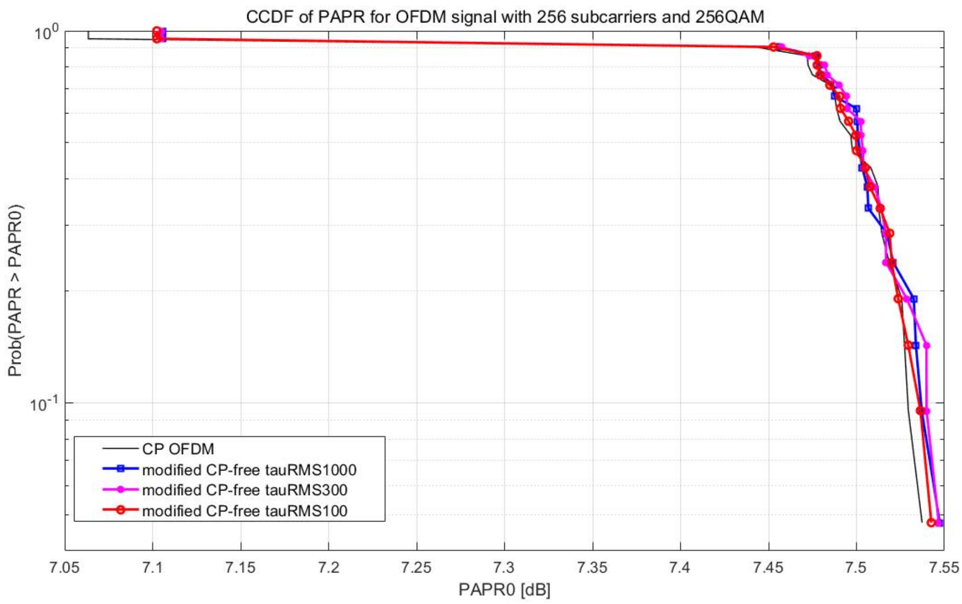
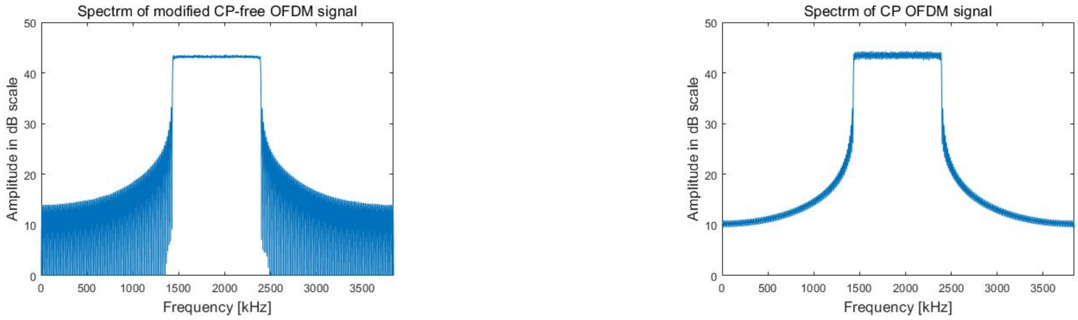


Figure 5.31. *PAPR of modified CP-free OFDM and 0-CP-OFDM with ideal TDL-D channel knowledge.*



(a) ***(b)***

Figure 5.32. *Spectrum comparison of modified CP-free OFDM (a) and CP-OFDM (b) with ideal TDL-D channel knowledge.*

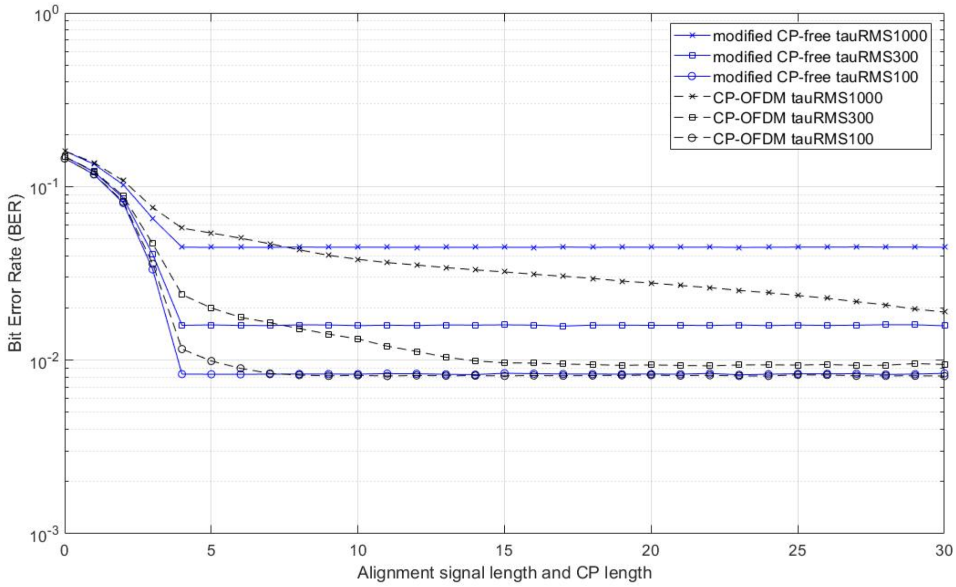


Figure 5.33. *Alignment signal length and CP length influence of modified CP-free OFDM and CP-OFDM with ideal TDL-D channel knowledge and Eb/No = 20 dB.*

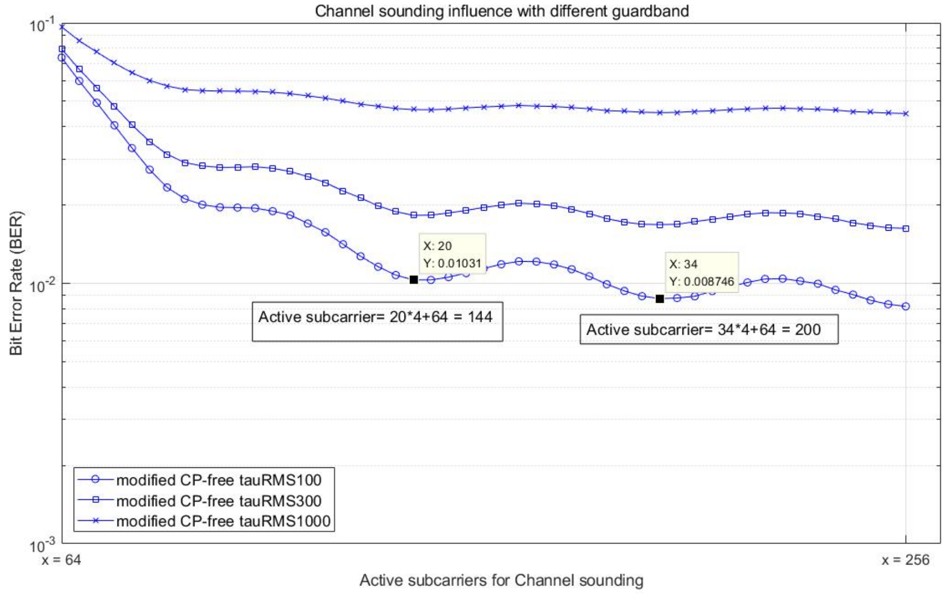


Figure 5.34. *The influence of channel knowledge bandwidth on the BER performance of modified CP-free OFDM and Eb/No = 20 dB.*

b) Full Band Channel Estimation

Table 5.8. *Parameters in full band channel estimation case*

Modulation Type	Modified CP-free OFDM & CP-OFDM
Channel Model	TDL-D, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	256
CP length	18
Alignment signal length	18
Channel knowledge in AS generation	Training symbol based
Active subcarriers / FFT size	256/256

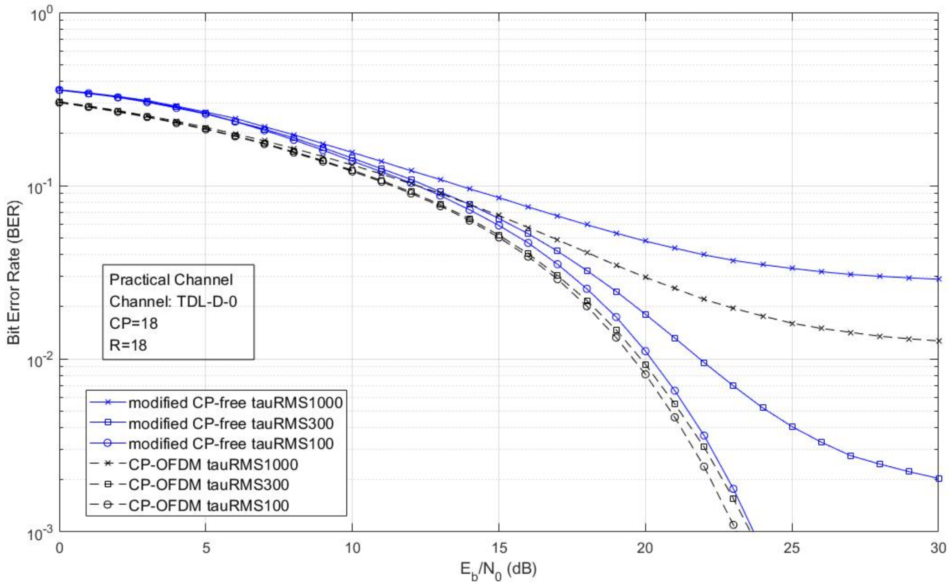


Figure 5.35. *BER Performance of Modified CP-free OFDM and CP-OFDM with full band channel estimation.*

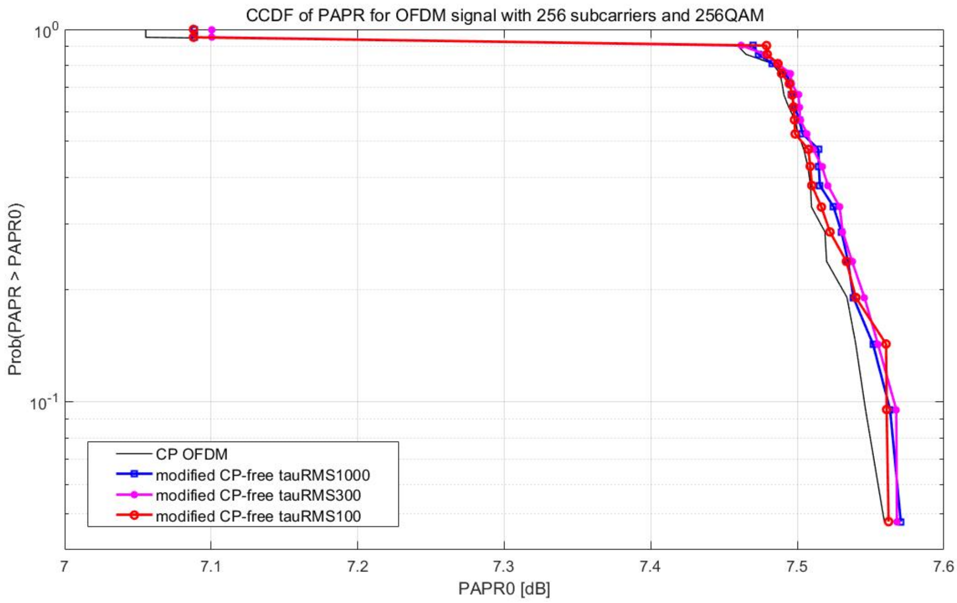
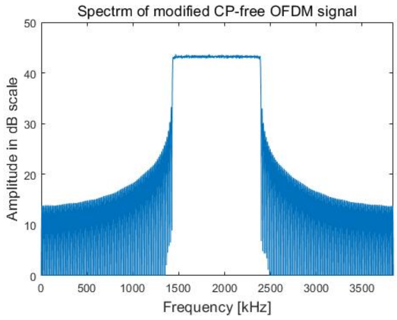
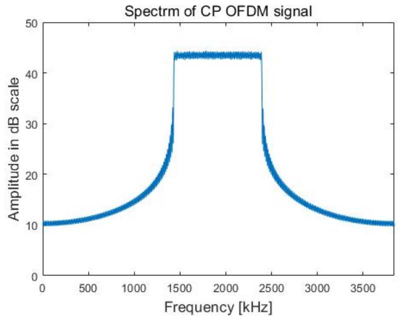


Figure 5.36. *PAPR of modified CP-free OFDM and CP-OFDM with full band channel estimation*





(a) ***(b)***

Figure 5.37. *Spectrum comparison of modified CP-free OFDM (a) and CP-OFDM (b) with fullband TDL-D channel knowledge.*

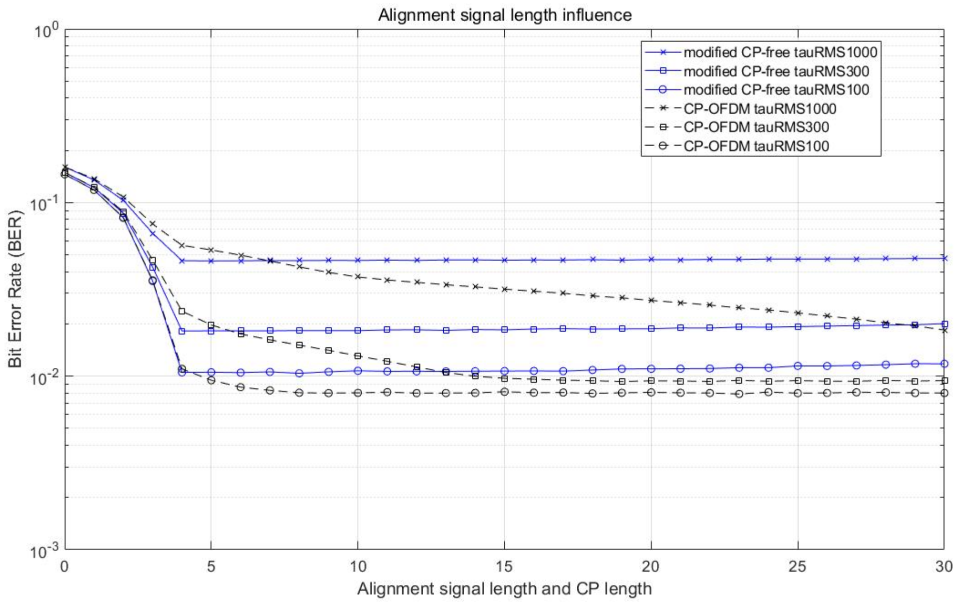


Figure 5.38. *Alignment signal length and CP length influence of modified CP-free OFDM and CP-OFDM with fullband TDL-D channel knowledge and Eb/No = 20 dB.*

Additional simulation results for the TDL-D channel are included in the Appendix, including also results for 64-QAM modulation and pre-equalization schemes. All simulations for TDL-D channel have been done with five scenarios, which are ideal channel knowledge, practical channel estimation, pilot boosting for channel estimation, pre-equalization with ideal channel knowledge and pre-equalization with pilot boosting. The alignment signal supports its function perfectly with short length in all five categories, and the PAPR of modified CP-free OFDM is only slightly higher than conventional CP-OFDM. Besides that, modified CP-free OFDM provides good performance while we increase the modulation order from 64 to 256 in the practical channel estimation scenario, which proves the functionality of alignment signal that generated with our new method.

Modified CP-free OFDM does not work as well as expected with TDL-D channel when using the pre-equalized scheme, even when we combined pilot boosting with pre-equalization.

Both with TDL-C and TDL-D channels, pre-equalization is not able to give significant benefit over the modified CP-free OFDM with channel equalization on the receiver side. However, the the effects of pre-equalization on the PAPR and transmitted PSD are greatly reduced in the TDL-D case compared to TDL-C.

6 CONCLUSION

With the aim for further improving OFDM technologies and adapting them into 5G NR and future applications, this thesis researches existing CP-free OFDM schemes and then provides a novel approach called modified CP-free OFDM. The main contributions and conclusions can be described as follows:

- Modified CP-free OFDM generates an alignment signal which has ISI canceling and circularity providing function without using a CP head to extend the symbol length. Thus, the spectral efficiency can be significantly improved by the proposed new design. Meanwhile, the simple equalization procedure of CP-OFDM is kept on the receiver side.
- Modified CP-free OFDM is developed based on the idea of Hamamreh and his team's CP-free OFDM methods [7]. The new design in this thesis calculates the alignment signal in the frequency domain with estimated channel information. The frequency-domain calculation efficiently avoids the problems for calculating the pseudo inverse matrix of channel convolution matrix, and the alignment signal length of modified CP-free OFDM is greatly reduced compared the CP-free methods of [7] using alignment signal length equal to the symbol length. Chapter 5 demonstrated, modified CP-free OFDM can greatly enhance the BER performance with practical channel.
- Modified CP-free OFDM has been tested in TDD-based SISO transmission scenarios using practical LOS and NLOS channel models. The simulation results of Chapter 5 illustrate that the proposed design provides decent performance with low delay profile (100 ns delay) in both TDL-D and TDL-C channels even with high modulation order, 64 for TDL-C and 256 for TDL-D. However, modified CP-free OFDM cannot provide as much good performance as conventional CP OFDM with medium and high delay profile, 300 ns and 1000 ns, respectively. With 300 ns delay spread, the performance is still decent with lower modulation orders. Thus, modified CP-free OFDM is a strong candidate for 5G and beyond service which need low latency and high spectral efficiency in both LOS and NLOS scenarios.
- The pre-equalized scheme for both modified CP-free OFDM and conventional CP-OFDM was tested in our simulation with TDL-C and TDL-D channel models. The pre-equalization schemes exhibit enhanced performance with ideal channel knowledge, but they tend to be very sensitive to channel estimation errors and cannot show any benefit even with pilot boosting. Furthermore, with frequency selective

channels, they distort the transmitted signal spectrum and increase PAPR. This would limit the usage of pre-equalization based schemes in the applications which are sensitive to high PAPR or need to rely on low quality channel estimation process.

- Channel estimation is a key element for alignment signal generation. For good performance, it is not enough to estimate the channel for the active subcarriers only. Initial results were obtained by assuming full-band channel knowledge or full-band channel estimate using OFDM training symbol with BPSK symbols in all subcarriers. Then the performance was evaluated with different channel knowledge bandwidths. It was found out that the channel knowledge bandwidth should be 50-100 subcarriers wider than the bandwidth of the active data subcarriers in the studied case with 64 active subcarriers and FFT-size of 256. Thus, modified CP-free OFDM still works well without the full channel band knowledge, which eases the requirements for channel estimation process.

6.1 FUTURE WORK

The proposed methods have been tested with two 5G channel models, and their functions have been proved in our simulations. But there are some aspects we have not explored yet, and those aspects will be tested and discussed in the future works and they can be described as follows: Finding better channel estimation methods for generating alignment signal. For obtaining better performance for modified CP-free OFDM, the methods we used in our simulations are conventional CP OFDM with training symbols which have active subcarriers outside the active data subcarriers. However, the OFDM signal needs a guard band to reduce the interference into the neighbor band due to the OOBE introduced by the OFDM modulation process. Thus, in our later research, not only OFDM based channel sounding techniques needed to be explored but also other time domain or frequency domain channel estimation approaches will be combined with modified CP-free OFDM. It is also important to study filtering with modified CP-free OFDM for reducing the OOBE. Results of Chapter 5 indicate that the OOBE is increased due to the alignment signal, especially with highly frequency-selective channels. So as to reduce the OOBE influence and further improve the performance for adapting new design into future applications, we will combine filtering with modified CP-free OFDM and check the performance. Besides the above two aspects, PAPR is still an issue in the modified CP-free OFDM, even though the PAPR increase is not very significant in our test cases. In order to adapt new designs onto UEs, further research about reducing PAPR is necessary. It is also necessary to consider the effects of mobility on modified CP-free OFDM since low latency and mobility are key elements for 5G cellular applications. Furthermore, the performance of modified CP-free OFDM should be evaluated with wide set of parameters in order to evaluate its feasibility for different services and communication scenarios.

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A APPENDIX

A.1 LOS conventional TDD SISO communication system

Ideal channel knowledge, 64 QAM

Modulation Type	Modified CP-free OFDM & CP OFDM
Channel Model	TDL-D, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	64
CP length	18
Alignment signal length	18
Channel knowledge in AS generation	Ideal channel knowledge
Active subcarriers / FFT size	256/256

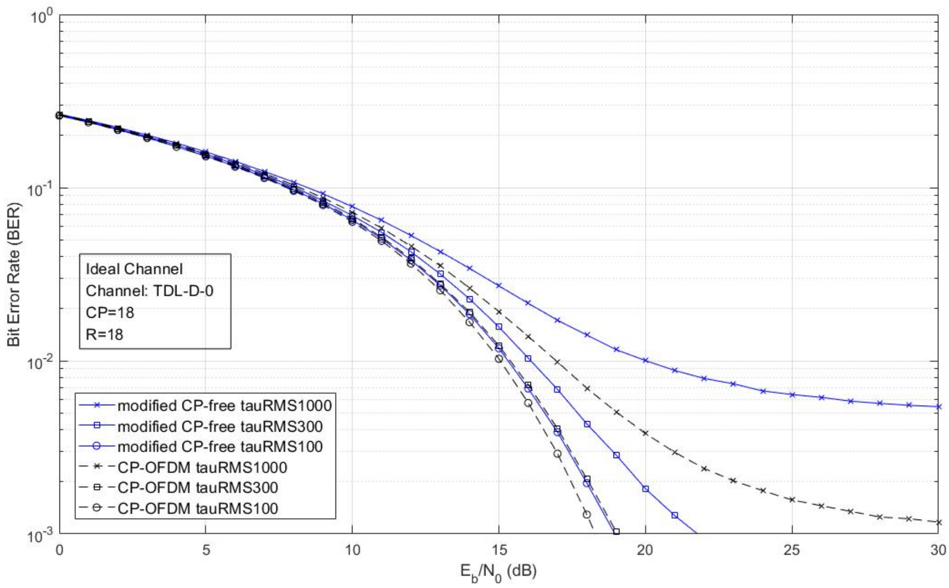


Figure A.1. *BER Performance of modified CP-free OFDM and CP-OFDM with ideal TDL-D channel knowledge.*

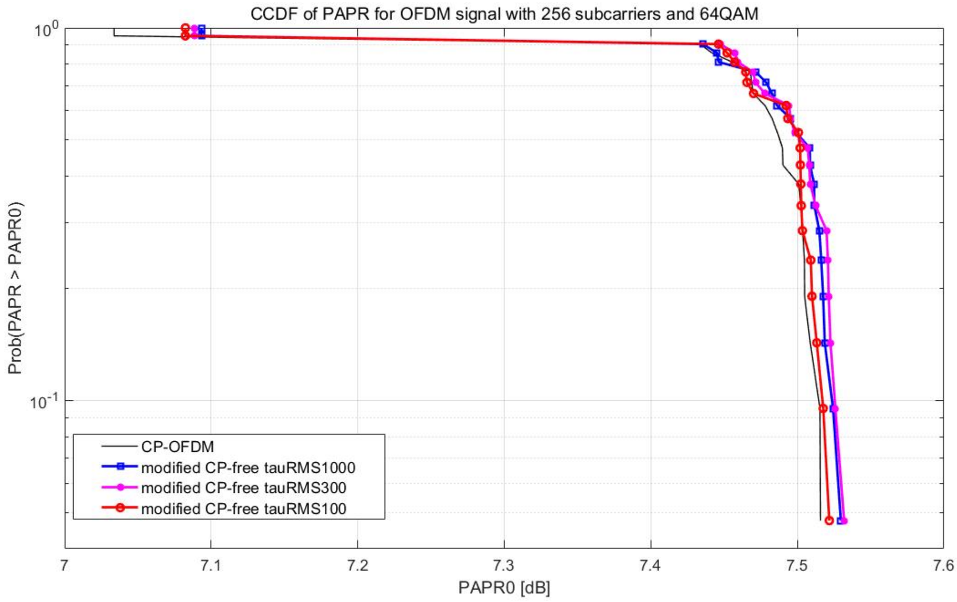


Figure A.2. *PAPR of modified CP-free OFDM and CP-OFDM with ideal TDL-D channel knowledge.*

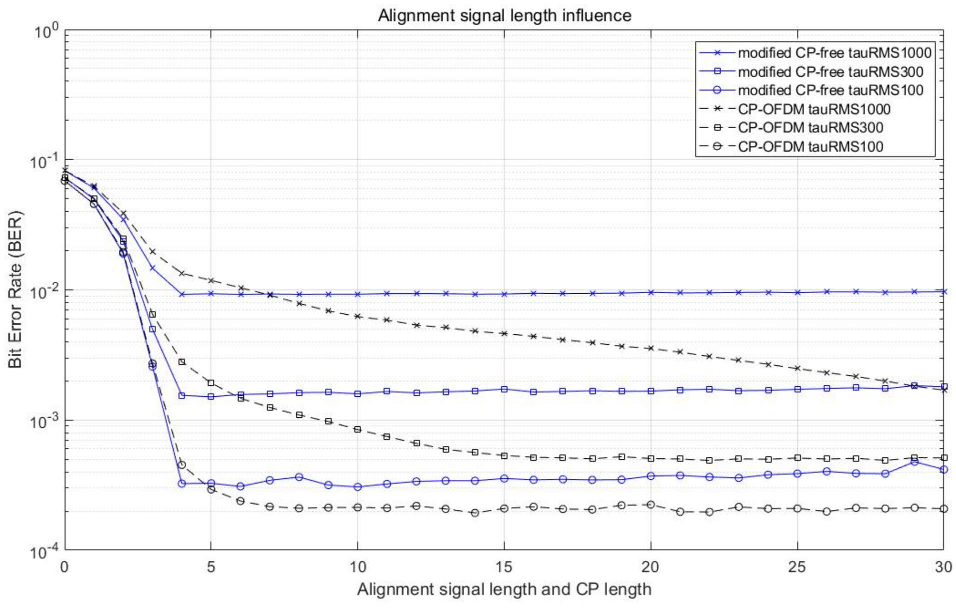


Figure A.3. *Alignment signal length and CP length influence of modified CP-free OFDM and CP-OFDM with ideal TDL-D channel knowledge and Eb/No = 20 dB.*

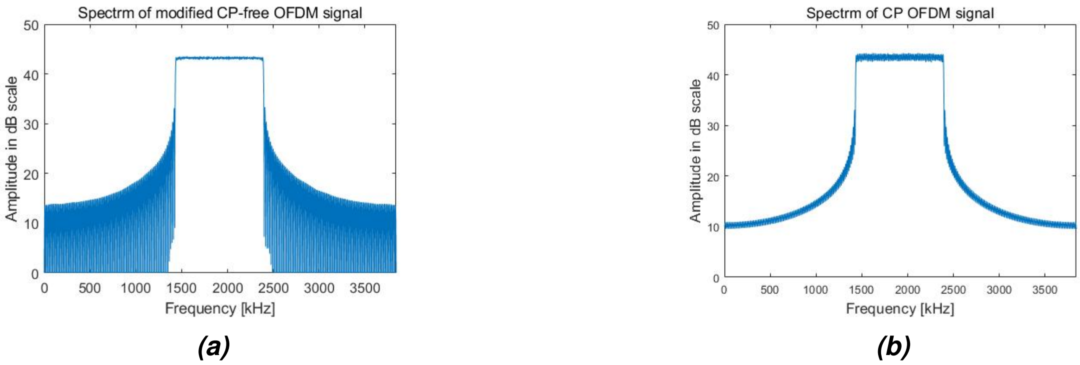


Figure A.4. *Spectrum comparison of modified CP-free OFDM (a) and CP-OFDM (b) with ideal TDL-D channel knowledge.*

Fullband channel estimation

Modulation Type	Modified CP-free OFDM & CP OFDM
Channel Model	TDL-D, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	64
CP length	18
Alignment signal length	18
Channel knowledge in AS generation	Training symbol based
Active subcarriers / FFT size	256/256

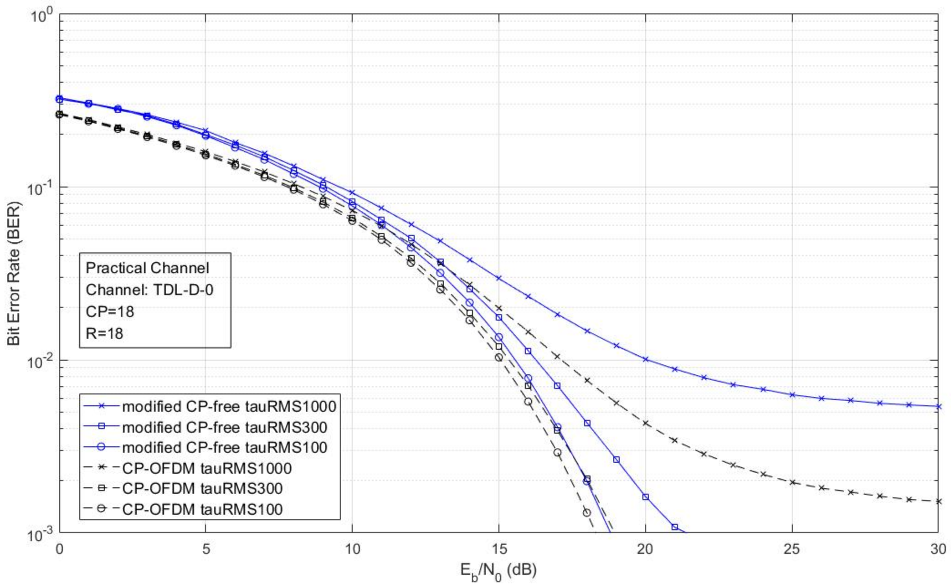


Figure A.5. *BER performance with modified CP-free and CP-OFDM with full band channel estimation.*

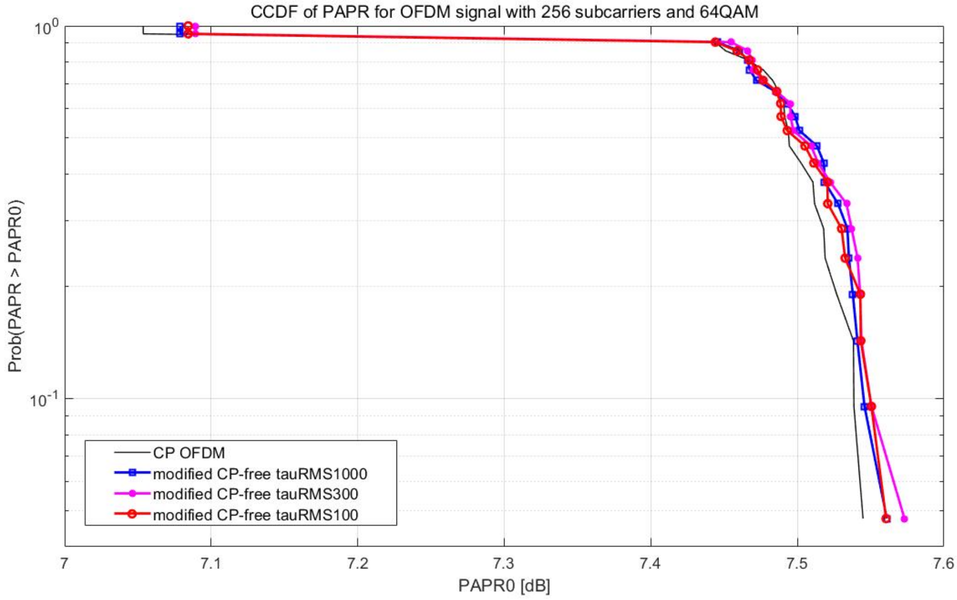


Figure A.6. *PAPR of modified CP-free and CP-OFDM full band channel estimation.*

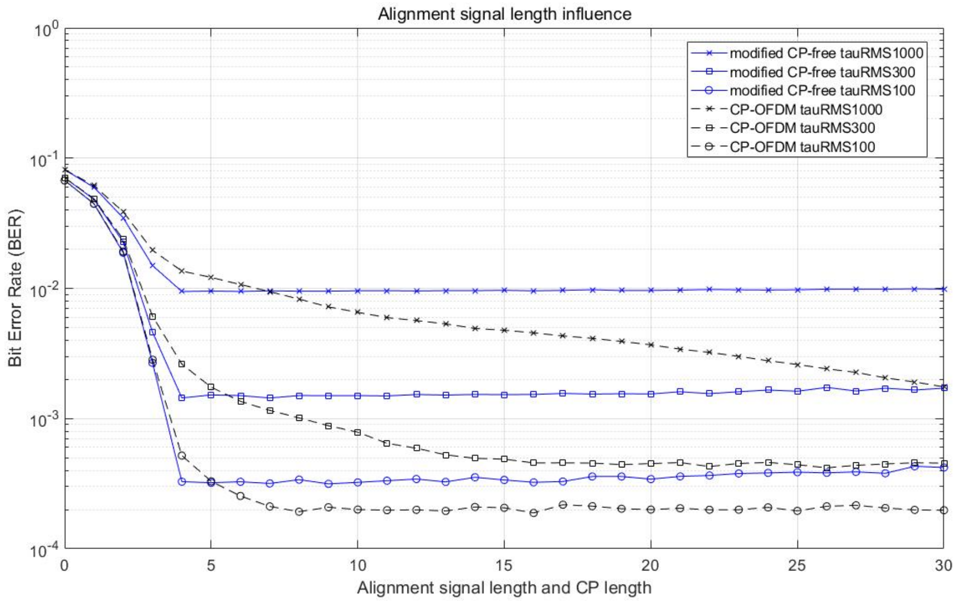
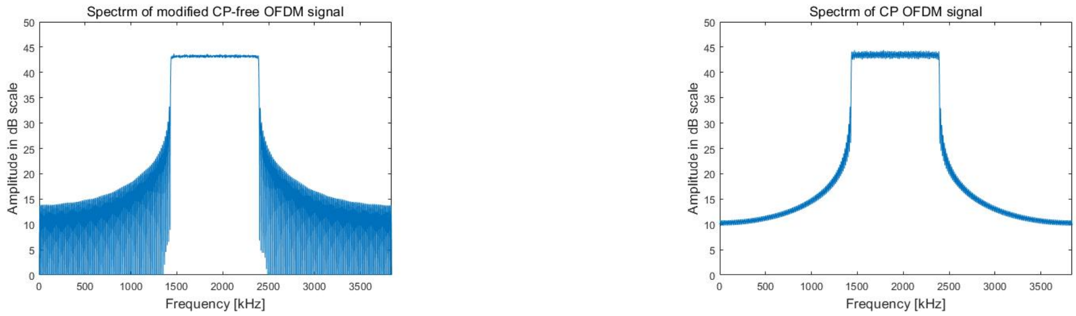


Figure A.7. *Alignment signal length and CP length influence of modified CP-free OFDM and CP-OFDM with fullband TDL-D channel knowledge and Eb/No = 20 dB.*



(a) *(b)*

Figure A.8. *Spectrum comparison of modified CP-free OFDM (a) and CP-OFDM (b) with fullband TDL-D channel knowledge.*

Pilot boosting channel estimation

Modulation Type	Modified CP-free OFDM & CP OFDM
Channel Model	TDL-D, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	64
CP length	18,0
Alignment signal length	18
Channel knowledge in AS generation	Training symbol based
Active subcarriers / FFT size	256/256

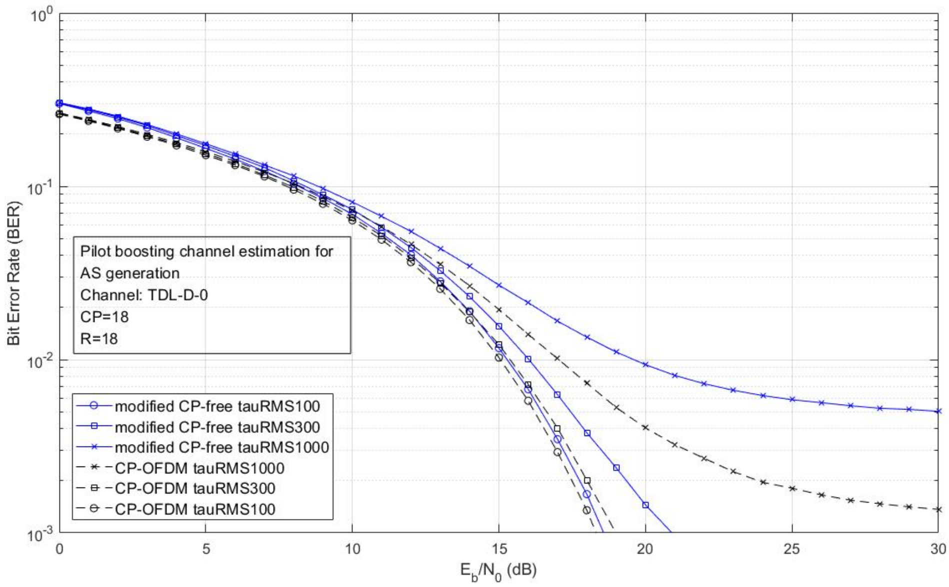


Figure A.9. *BER Performance of modified CP-free and CP-OFDM with pilot boosting TDL-D channel estimation.*

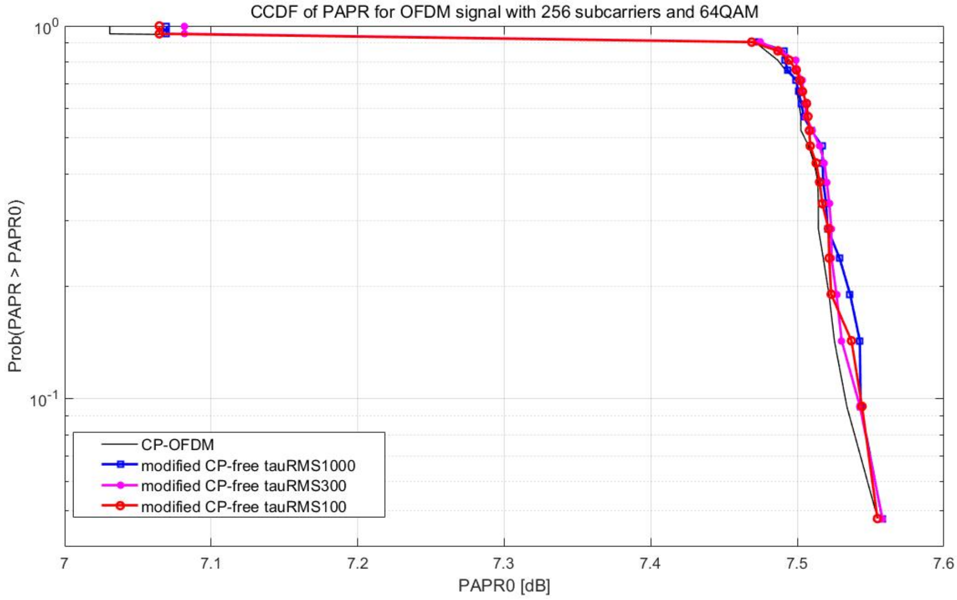


Figure A.10. *PAPR of modified CP-free and CP-OFDM with pilot boosting TDL-D channel estimation.*

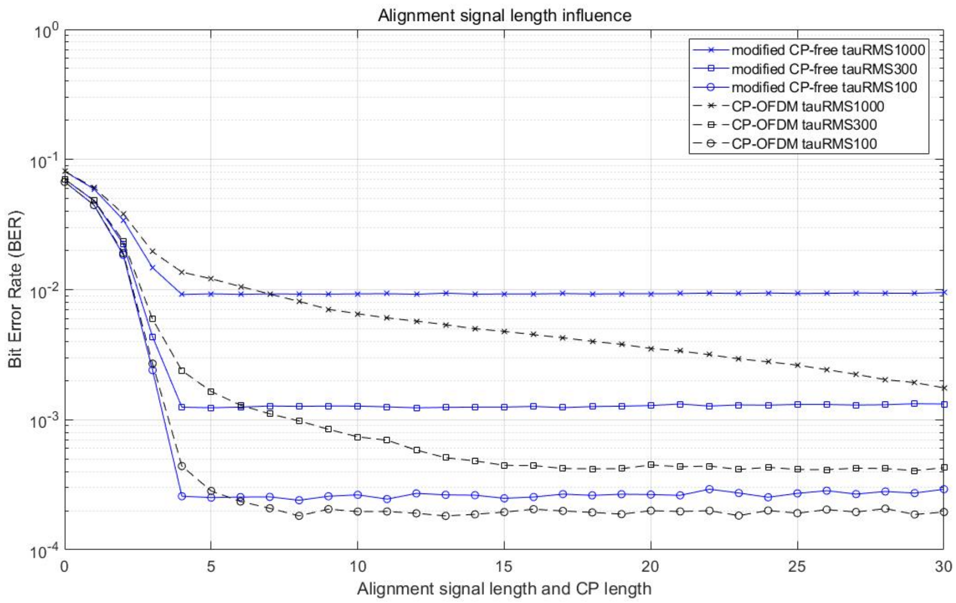
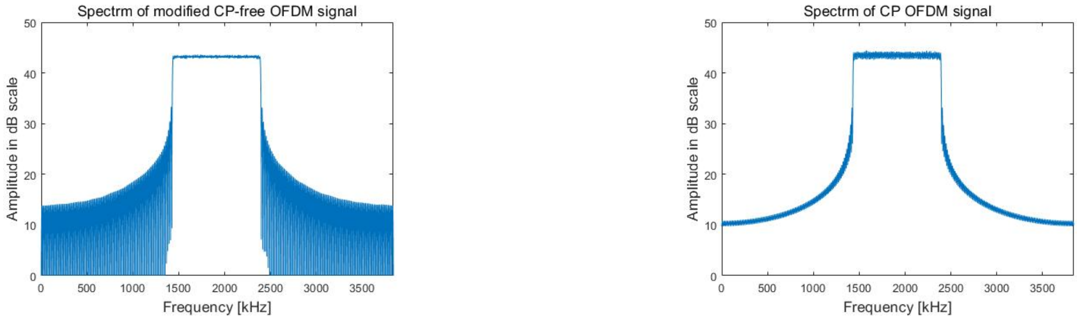


Figure A.11. *Alignment signal length and CP length influence of modified CP-free OFDM and CP-OFDM with pilot boosting TDL-D channel estimation and Eb/No = 20 dB.*



(a) ***(b)***

Figure A.12. *Spectrum comparison of modified CP-free OFDM (a) and CP-OFDM (b) with pilot boosting TDL-D channel estimation.*

Pre-equalized scheme with ideal channel knowledge

Modulation Type	Pre-equalized modified CP-free OFDM Pre-equalized CP OFDM
Channel Model	TDL-D, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	64
CP length	18,0
Alignment signal length	18
Channel knowledge in AS generation	Ideal channel knowledge
Active subcarriers / FFT size	256/256

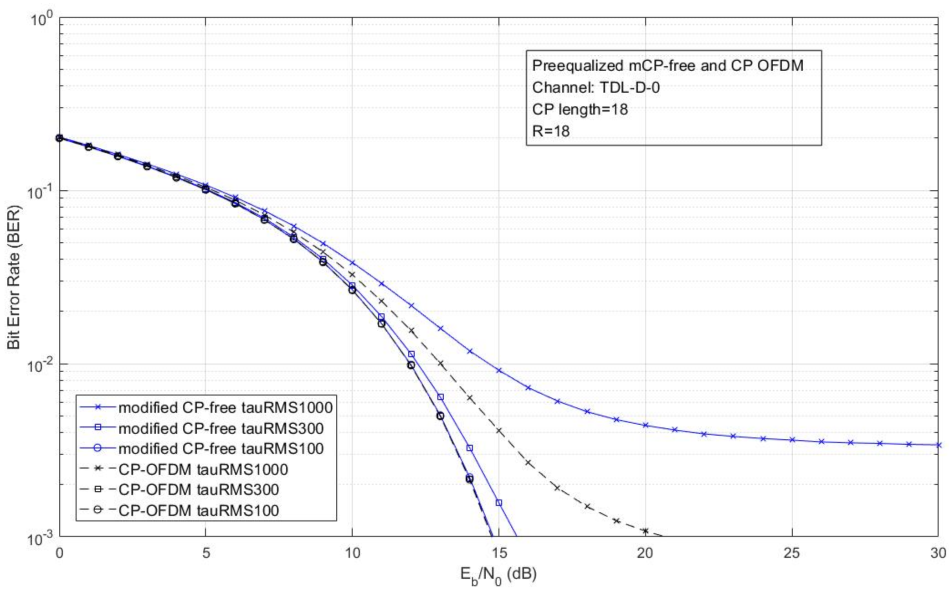


Figure A.13. *BER performance of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with ideal channel knowledge.*

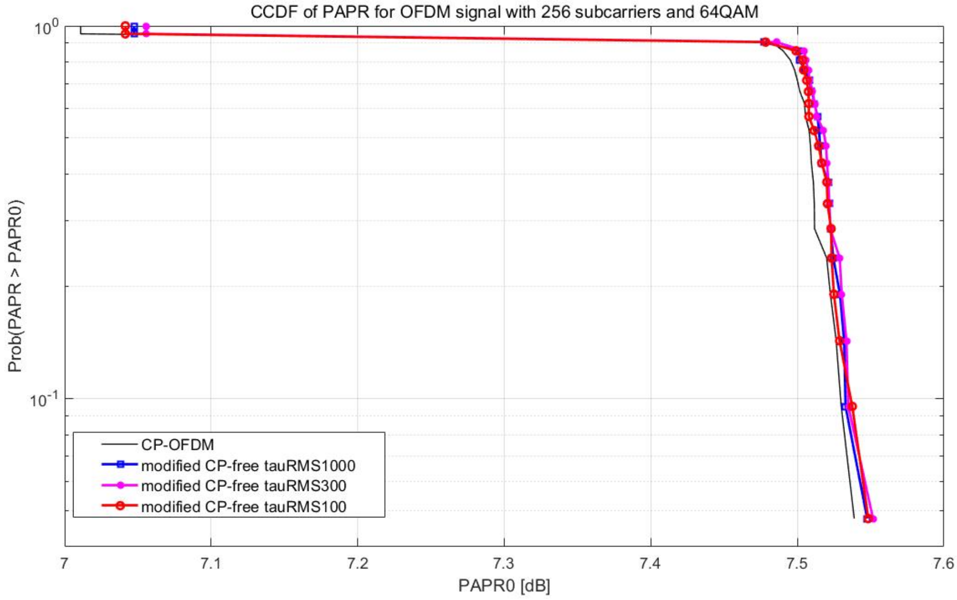


Figure A.14. *PAPR of pre-equalized modified CP-free and pre-equalized CP-OFDM with ideal TDL-D channel.*

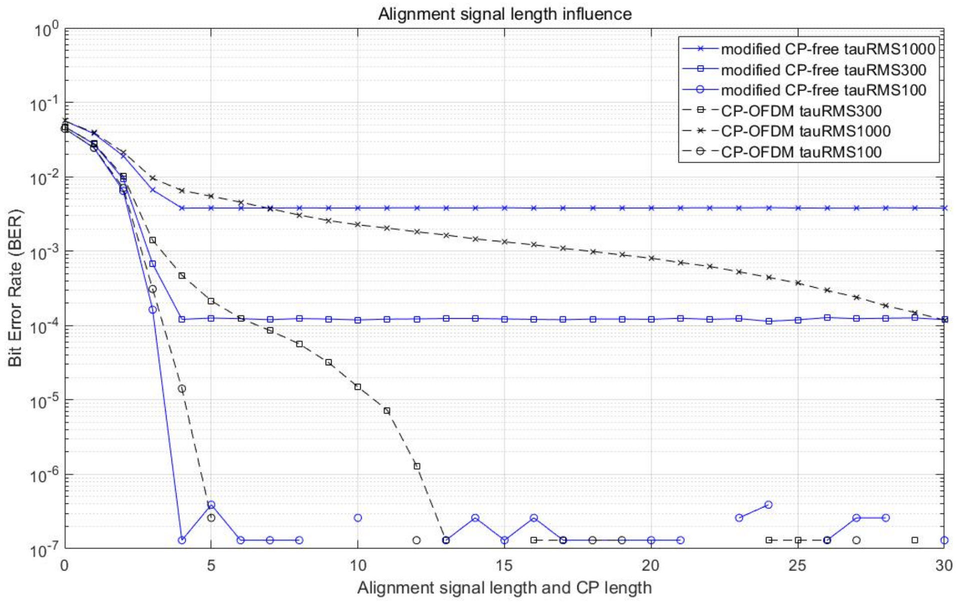
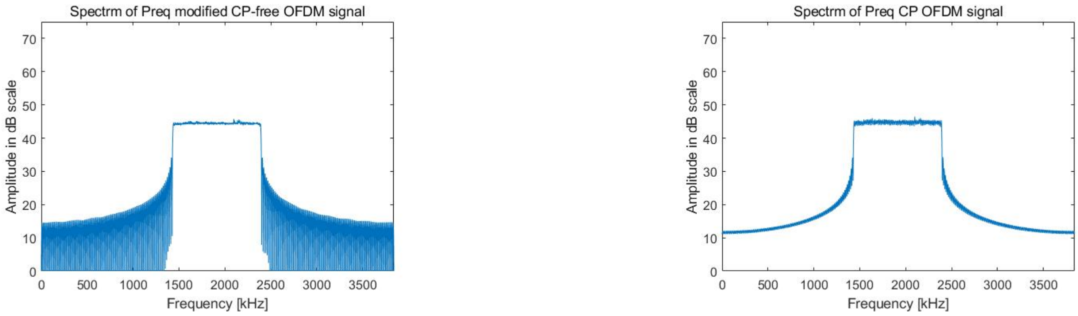


Figure A.15. *Alignment signal length and CP length influence of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with ideal TDL-D channel knowledge and Eb/No = 20 dB.*



(a) *(b)*

Figure A.16. *Spectrum comparison of pre-equalized modified CP-free OFDM (a) and pre-equalized CP-OFDM (b) with pilot boosting TDL-D channel estimation.*

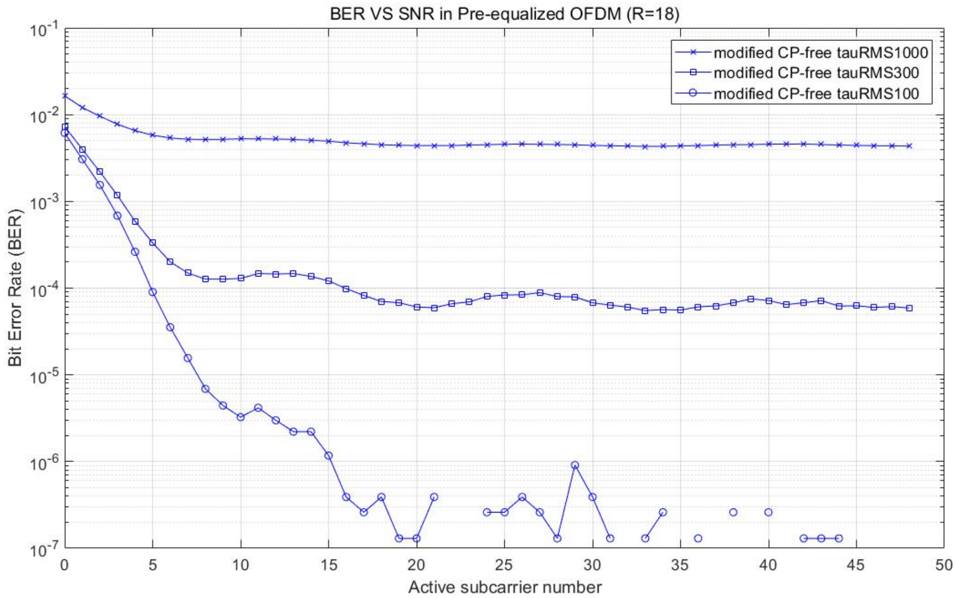


Figure A.17. *Activer subcarrier number influence of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with ideal channel knowledge and Eb/No = 20 dB.*

Pre-equalized scheme with ideal channel knowledge

Modulation Type	Pre-equalized modified CP-free OFDM Pre-equalized CP OFDM
Channel Model	TDL-D, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	256
CP length	18,0
Alignment signal length	18
Channel knowledge in AS generation	Ideal channel knowledge
Active subcarriers / FFT size	256/256

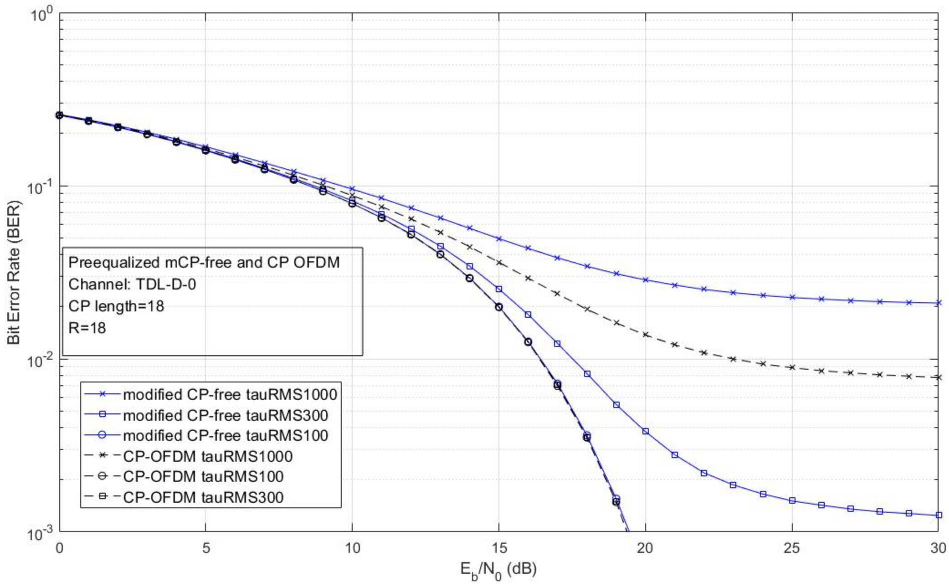


Figure A.18. *BER performance of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with ideal channel knowledge*

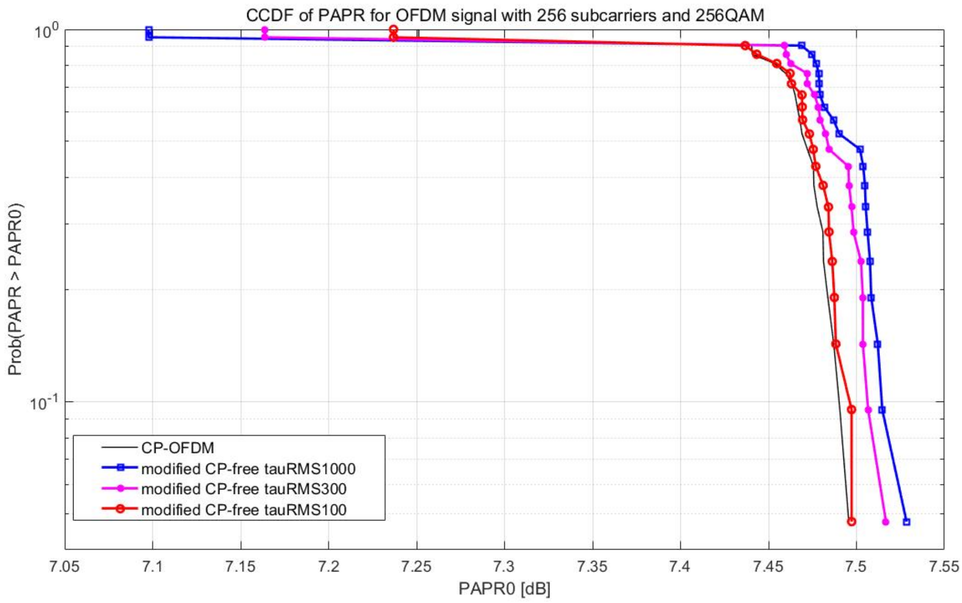


Figure A.19. *PAPR of pre-equalized modified CP-free and pre-equalized CP-OFDM with ideal TDL-D channel.*

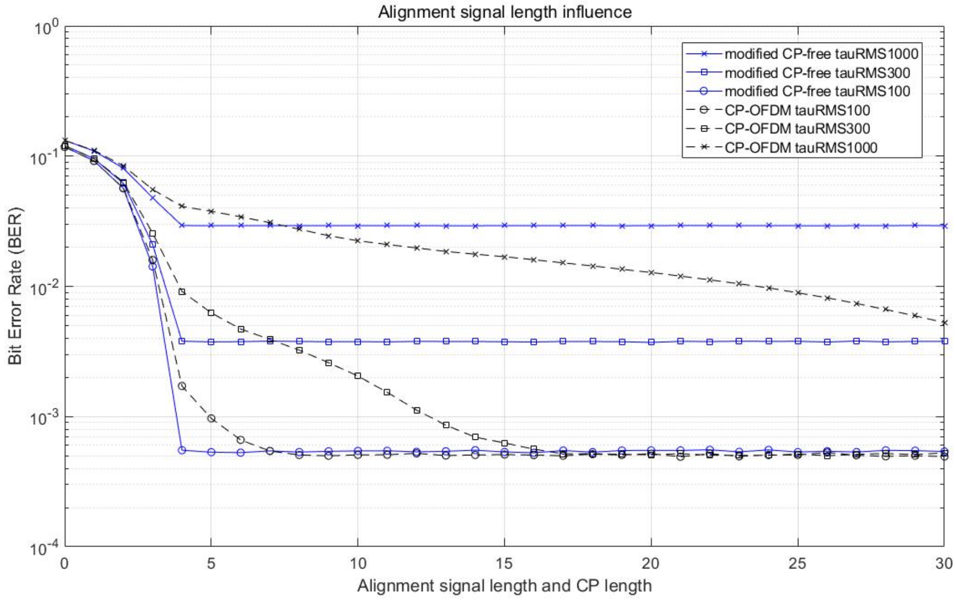


Figure A.20. *Alignment signal length and CP length influence of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with ideal TDL-D channel knowledge and Eb/No = 20 dB.*

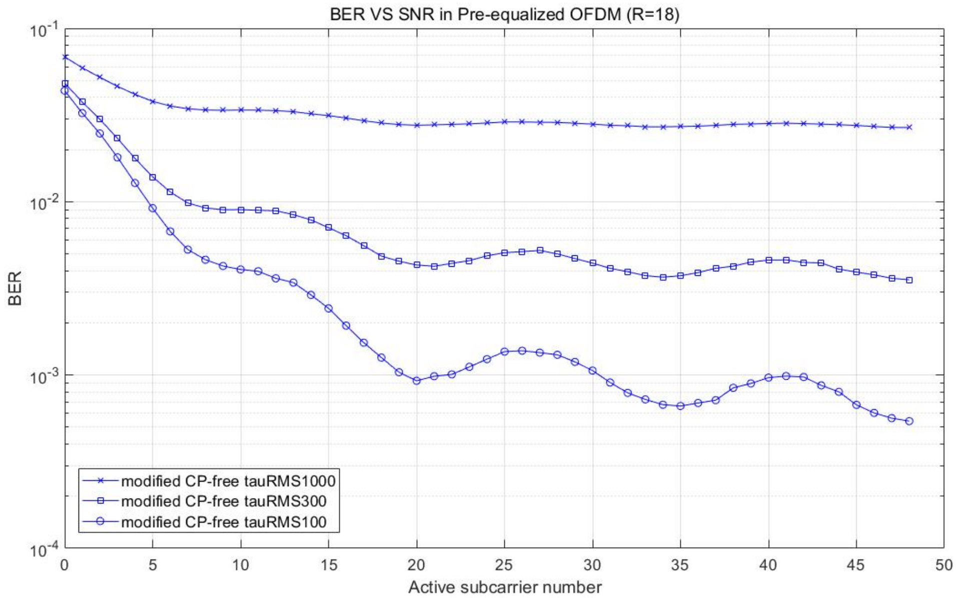


Figure A.21. *Active subcarrier number influence of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with ideal channel knowledge and Eb/No = 20 dB.*

Pre-equalized scheme with pilot boosting channel estimation

Modulation Type	Pre-equalized modified CP-free OFDM Pre-equalized CP-OFDM
Channel Model	TDL-D, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	64
CP length	18,0
Alignment signal length	18
Channel knowledge in AS generation	Training symbol based
Active subcarriers / FFT size	256/256

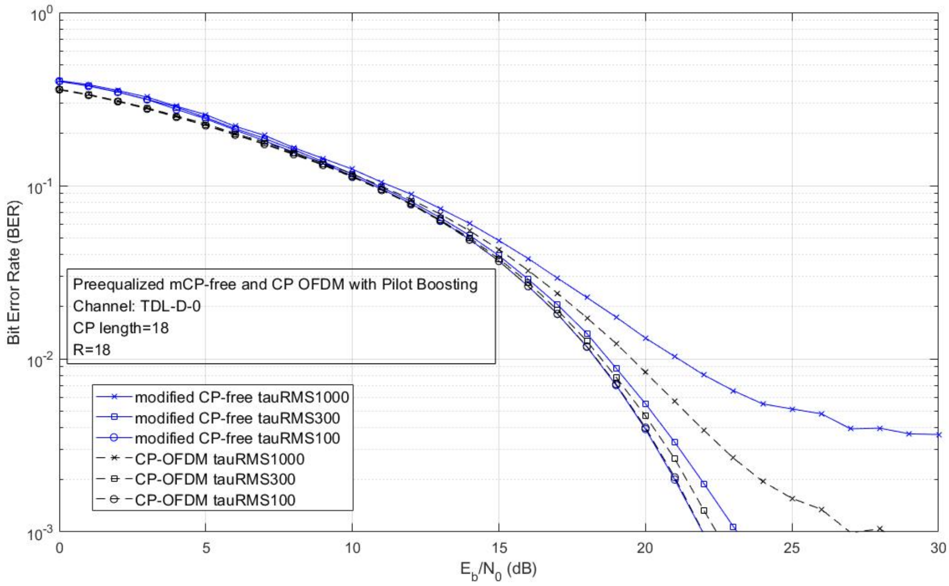


Figure A.22. *BER performance of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with pilot boosting TDL-D channel estimation.*

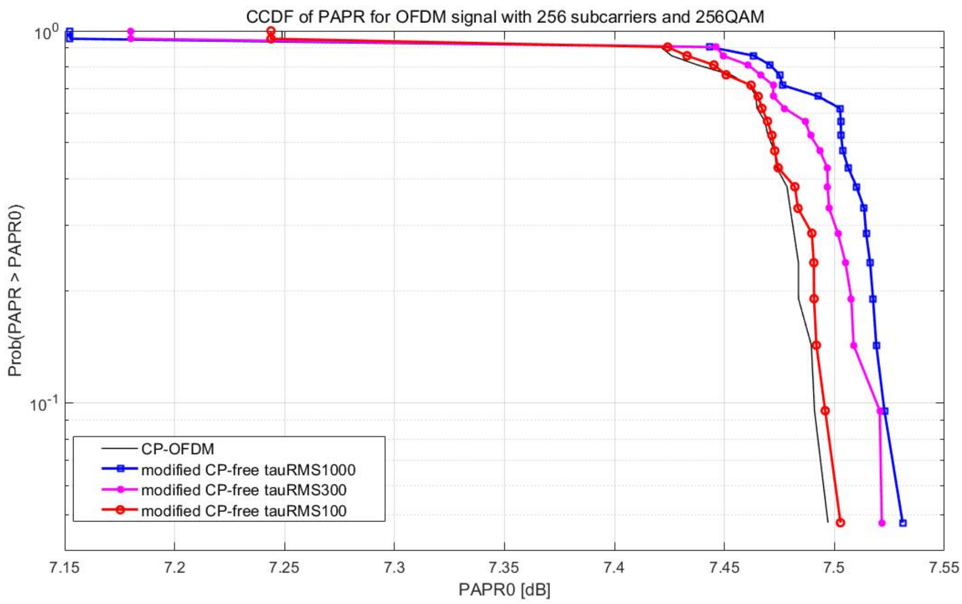


Figure A.23. *PAPR of pre-equalized modified CP-free OFDM and pre-equalized CP-OFDM with pilot boosting TDL-D channel estimation.*

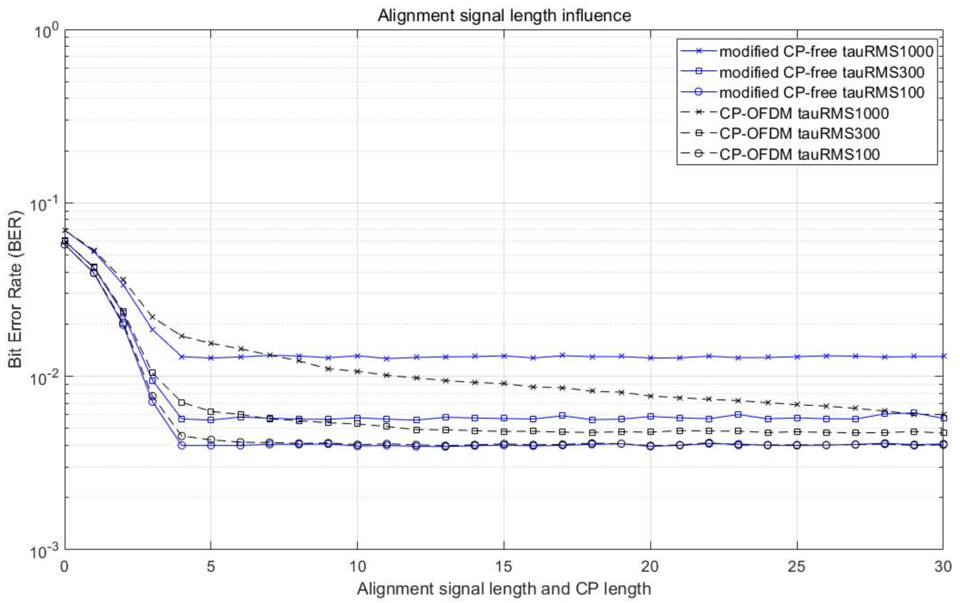
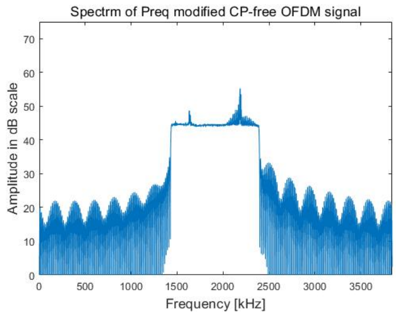
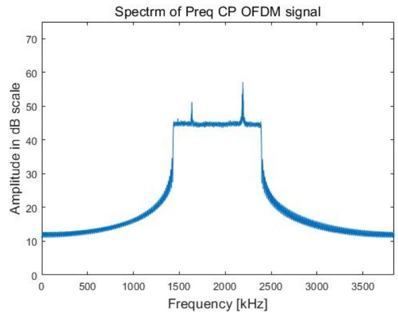


Figure A.24. *CP and alignment signal influence of pre-equalized modified CP-free and pre-equalized CP-OFDM with pilot boosting TDL-D channel estimation and Eb/No = 20 dB.*



(a)



(b)

Figure A.25. *Spectrum comparison of pre-equalized modified CP-free OFDM (a) and pre-equalized CP-OFDM (b) with pilot boosting TDL-D channel estimation.*

Pre-equalized Scheme with Pilot Boosting Channel Estimation

Modulation Type	Pre-equalized modified CP-free OFDM Pre-equalized CP OFDM
Channel Model	TDL-D, zero mobility, 100, 300, 1000 ns RMS delay spread
Active subcarriers / FFT size	64/256
Modulation order	256
CP length	18,0
Alignment signal length	18
Channel knowledge in AS generation	Training symbol based
Active subcarriers / FFT size	256/256

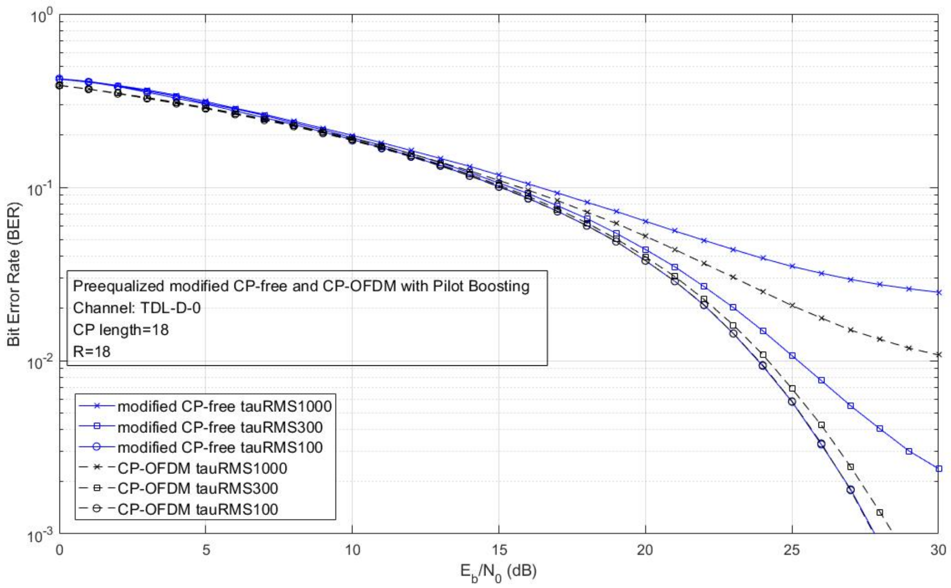


Figure A.26. *BER performance of pre-equalized modified CP-free OFDM and prequalized CP-OFDM with pilot boosting TDL-D channel estimation.*