JOURNAL OF SCIENCE
SAKARYA UNIVERSITY

Sakarya University Journal of Science

ISSN 1301-4048 | e-ISSN 2147-835X | Period Bimonthly | Founded: 1997 | Publisher Sakarya University | http://www.saujs.sakarya.edu.tr/

Title: Implementation of Polar Codes in 5G Systems with Different Waveform Modulations by Using USRP

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Recieved: 2019-03-06 19:02:23

Accepted: 2019-07-16 15:19:18

Article Type: Research Article
Volume: 23
Issue: 6
Month: December
Year: 2019
Pages: 1144-1153

How to cite
Marwan Dhuheir, Sıtkı Öztürk; (2019), Implementation of Polar Codes in 5G Systems with Different Waveform Modulations by Using USRP. Sakarya University Journal of Science, 23(6), 1144-1153, DOI: 10.16984/saufenbilder.536540
Access link
http://www.saujs.sakarya.edu.tr/issue/44246/536540

Sakarya University Journal of Science 23(6), 1144-1153, 2019

Implementation of Polar Codes in 5G Systems with Different Waveform Modulations by Using USRP

Marwan DHUHEIR*[1], Sıtkı ÖZTÜRK[2]

Abstract

Long Term Evolution (LTE) is an access technique that is used in radio networks. LTE provides high data bandwidth in transmitting data by providing flexibility against noise and interference. Orthogonal Frequency Division Multiplexing (OFDM) technique uses the FDM (Frequency Division Multiplexer) modulation technique to increase the amount of carried information over the wireless network. The OFDM signal is transmitted to the receiver at different frequencies which they are orthogonal to each other by dividing the bandwidth of a signal into smaller sub-carriers. Recently, the use of polar codes as a coding scheme in the new generation 5G systems has come to the communications markets. Polar codes as a channel coding scheme are a promising technique for the future because it is the first codes that reach Shannon capacity limit. The cyclical prefix – OFDM (CP-OFDM), which is used in 4G systems, performs well in many aspects, however, it has much weakness that make the researches look for a new modulation technique to be used in 5G systems. Filtered–OFDM (F-OFDM) is considered one solution to the problems appeared in CP–OFDM. In this paper, the differences between CP-OFDM and F-OFDM regarding advantages and disadvantages of each type are studied in details. The comparison between the two modulations waveforms are done by studying their Error Vector Magnitude (EVM) that deals with measuring the accuracy of the received signals. Furthermore, the comparison between the two modulations waveforms with polar codes in the USRP B210 radio are applied to make our work more practical.

Keywords: Polar Codes, USRP, CP-OFDM, F-OFDM.

1. INTRODUCTION

Coding and modulation are considered the most two important factors in the communication channel coding theorem. Unfortunately, information sent over a noisy channel is inevitably affected by any kind of noise. One of the most important questions in the channel coding theorem is at what rate we can send information reliably through any noisy channel. One way to recover the data sent correctly or with negligible errors is to add redundancy bits. This method is known as channel coding, and it is crucial in communication systems. An effective

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coding method is the one that adds redundancy bits in case of having high code rate and gets a low error. Shannon in [1] defined the rate of transmitting data reliably over a channel. This theorem is known as "the channel coding theorem". One important issue is how to design a practical code that achieves the Shannon capacity limit. Polar codes are provably the first codes that achieve the limit of Shannon capacity. Polar codes belong to the class of capacity-achieving linear Forward Error Correction (FEC) block codes with encoding and decoding complexity of $O(NlogN)$, in which N refers to the code block-length. The block error probability of the Successive Cancellation (SC) decoder is approximately less than $2^{(-\sqrt{N})}$ [2]. Constructing polar codes is done by transforming the physical channel into virtual channels. The virtual channels are distributed into either good channels or bad channels. In other words, the channels are polarized into perfect channels that have high channel capacities or useless channels that have low channel capacities. Moreover, in this paper, we don't give details about polar codes for an introduction, we recommend referring to [2], [3], [4].

OFDM is an encouraging technique for getting high-data-rate that is required by the telecommunication engineers as it might defeat inter-symbol interference (ISI) that is come from the multipath fading in the wireless channels. OFDM is considered a set of two techniques which are modulation and multiplexing. Modulation refers to the method of mixing the information on changes occurred in the carrier signal. This carrier might be in phase, frequency or amplitude or a combination of them. Multiplexing refers to the signals that are independent of each other and come from various sources; therefore we care about sharing spectrum with many users. In OFDM, the independent signals actually are a sub-set of the main signal. However, the main signal is divided into different channels, then modulated by the data and again go to the multiplexing step in order to get OFDM carrier signal. OFDM is considered a special case of FDM. To explain the concept FDM and OFDM, we can think that a FDM signal is like water flow coming by faucet and OFDM is like water coming from the shower as in Figure 1.

Figure 1. (a) Regular FDM single carrier, all water comes from the single big faucet (b) OFDM, the same amount of water comes from different holes [5]

In case of water coming from the faucet, all water flows through a single big stream which cannot be split into subsets. On the other hand, we can think of the shower is like OFDM which the signal is divided into sub-sets. In the case of the faucet, if we put the thumb over the hole, the water will be stopped from flowing, while in case of the shower, if we do the same though, the water will not be stopped and will be still flowing. This means if there is interference in the FDM, the signal will be obstructed, however in the case of OFDM, it will be possible to send the data.

OFDM is considered one special case of multicarrier modulation technique [6], and it was used firstly in the military section. It was Weinstein in 1971 who carried out OFDM by the means of a Discrete-time Fourier Transform (DFT) [7]. Its computational process was very complicated and it was simplified by a Fast Fourier Transform (FFT). In first days, OFDM was not commonly used because of the expense in FFTs' execution and VLSI technologies offered easy and cheap execution of FFTs and IFFTs. It was Cimini, in the 1980s, who explored the use of OFDM technique in the field of wireless communication [8]. In the years of 1990s, OFDM stated to get in many sides of technologies including by Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), Asymmetric Digital Subscriber Line (ADSL) and IEEE802.11a. The main objective of OFDM is to mitigate the ISI caused by multipath fading, therefore, the whole channel is divided into sub-channels and the total data rate is transmitted in the small sub-channels. This gives us an advantage of sending data in N times greater compared to a single big carrier channel.

Although the OFDM systems offer the solution for the interference, it has two drawbacks that make us look for another solution to mitigate the interference; the first drawback is the large Peak-to-Average Power Ratio (PAPR). The big difference between OFDM and regular FDM with a single carrier in the PAPR gives us a nonlinear distortion of the sent signal. Therefore this decreases the efficiency of many devices such as power amplifiers. The drawback of OFDM is the sensitivity to two main parameters, one is Doppler frequency and the other is the carrier offset of the signal as they related to the sub-channels bandwidth which the bandwidth between them is very small. Since the space between the sub-channels is very small, any small variation in the OFDM symbol or frequency offset will be destroyed and gives us another problem which is Inter-Carrier Interference (ICI) [9], [10].

One of the main advantages of OFDM over single-carrier patterns is the ability to deal with multiple channel conditions while there is no need for complex equalization filters. In OFDM, the channel equalization is simple because it deals with small modulated narrow-band signals rather than just only one modulated signal as in single carrier schemes. The narrowband carrier rates take the advantage of guard intervals between symbols affordable and this guard helps delete the noise such as ISI, mitigate echoes and time spreading to offer the property of diversity that helps improve Signal to Noise Ratio (SNR).

2. CP-OFDM AND F-OFDM

CP that transmitted during the guard interval contains the copy data of the end of OFDM signal. The advantage of copying the end of OFDM signal is that at the receiver side, the receiver will be able to integrate over a specific number of sinusoid cycles for every multipath signal at OFDM demodulation process with FFT. Figure 2 demonstrates the conventional OFDM in which the input symbols are modulated by using IFFT then CP is added to the output samples.

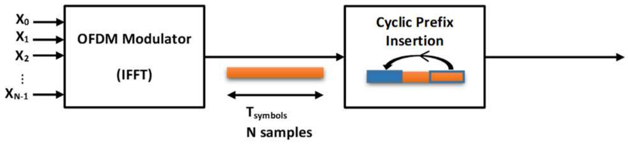

Figure 2. Conventional OFDM

F-OFDM is a technique of using filters to sub-band carriers. This method helps conventional CP-OFDM increase the system flexibility. However, it has a disadvantage of increasing system complexity.

2.1. CP-OFDM

The most important point of OFDM is to use low symbol rate schemes in parallel instead of sending one single symbol modulation scheme which suffer from ISI caused by many sources such as multipath propagations. Each symbol is long and to prevent ISI, it is suggested to insert a guard interval between symbols. This guard has many advantages such as decreasing the sensitivity of devices to time synchronization and eliminating the filters like a pulse shaping filter.

One simple example is that suppose one million symbols per second is sent over a channel by using single carrier modulation, the duration period of symbols is equivalent to one microseconds or less. This exposes that synchronization will be difficult and the interference is high. If the same amount of data is applied to one thousand sub-channels, then duration period of every symbol rate will be longer by amount of a thousand i.e. one millisecond for orthogonal symbols where the bandwidth is the same. Let us suppose that there is 1/8 a guard interval between every symbols. ISI could be mitigated in case of multipath time spreading, which is the measured time between the first received symbol and the last echo signal, is shorter than the guard interval i.e. 125 microseconds. This equivalents to maximum difference of 37.5 km which is the length of the paths [11].

2.2. F-OFDM

Technologies related to physical layer of wireless communication is introduced recently such as waveform modulation. CP-OFDM has many advantages such as it offers high efficiency, its implementation is simple and it can be combined with MIMO technology easily, etc., so it was adopted in 4G-LTE, Wi-Fi and many wireless communication technologies. However, it has disadvantages such as out-of-band power leakage, it requires high quality requirements for synchronization, and the whole bandwidth could be created by the same waveform parameters, i.e. the subcarrier spacing and CP length.

As 4G, 5G needs to support more diverse traffics shapes. Moreover, in 5G, different scenario of traffics should be considered such as the traffics that come from vehicle to vehicle and the low cost machines' traffics and at the same time it should preserve the same advantages of conventional CP-OFDM.

Therefore F-OFDM was introduced. F-OFDM works by applying sub-band filtering on CP-OFDM in which it could meet the required improvement for 5G systems. The bandwidth is divided to into sub-bands and each band is filtered separately. Each sub-band is configured with various waveforms parameters set according to the existed traffic scenario. During the process of filter configuration, every sub-band is configured independently and creates 5G waveform that has the ability to provide dynamic parameter configuration for the physical layer according to the specific traffic scenario. The frequency spacing between the subcarriers might be different with every sub-band. By using this method, we can get a flexible structure of sub-frames that contain many types of data services in the same sub-frame. It is supposed to adopt this flexible waveform structure to 5G systems. Figure 3 explains the configuration of F-OFDM. The sub-band samples are gathered together in order to add the required filter to them.

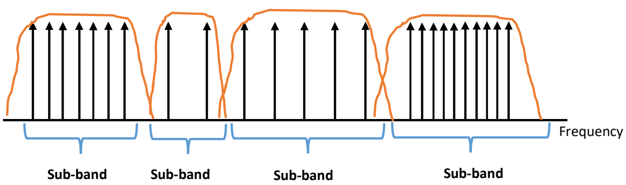

Figure 3. F-OFDM configuration

Figure 4 shows a comparison between conventional CP-OFDM and F-OFDM. In CP-OFDM, the whole band is configured from a single block and the frequency spacing between every sub-carrier is the same. However, in F-OFDM, the whole band is created from various sub-blocks. Moreover, the space frequency between sub-bands is also different i.e. the space frequency of sub-carrier for N_1 is Δf/2 and the space frequency of the sub-carrier N_k is 4Δf. We can see that each sub-band has its own CP and each sub-band has its own filter.

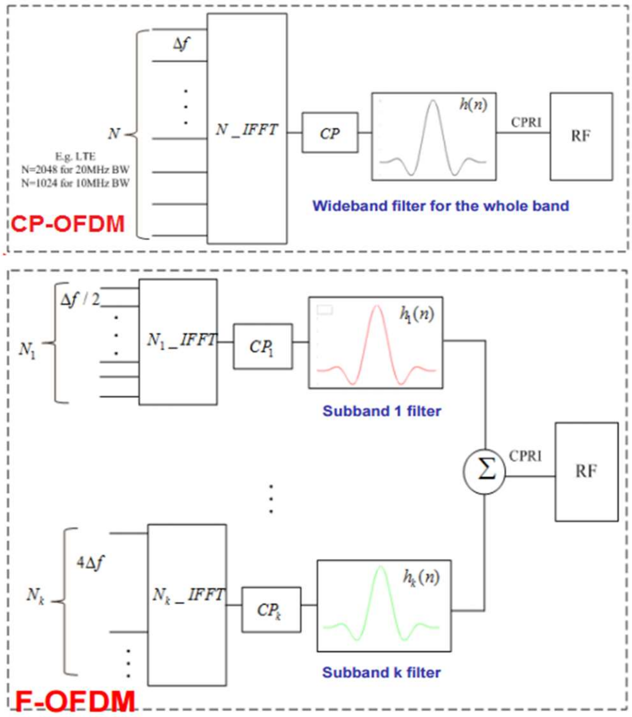

Figure 4. CP-OFDM and F-OFDM comparison [12]

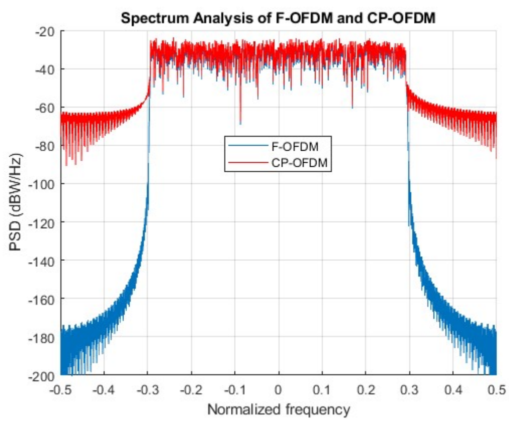

Figure 5. CP-OFDM and F-OFDM spectrum analysis comparison

We can mention that the main advantage of F-OFDM is the flexibility that it provides and the main disadvantage is that its complexity of the structure and implementation is higher than that achieved by CP-OFDM.

Figure 5 shows the comparison between CP-OFDM and F-OFDM in case of spectrum analysis. From the figure, it is clear that F-OFDM has a betterr resistance against noise.

3. TRANSMISSION AND RECEPTION USING POLAR CODES WITH CP-OFDM AND F-OFDM IN USRP RADIO DEVICE

In this part, we used two USRP radios to send data from one device and receive it in the other device with using polar codes as a channel coding scheme. We used LTE- MIMO system to do the experiment in which MIMO 2×2 was used with the diversity property as shown in Figure 6. We sent the string "Kocaeli University" from one USRP device and successfully received it in the other USRP device. We started the work by not introducing any external noise and left the environment noise just only and successfully received the data. In the next step, we added AWGN to the received signal and it was successfully decoded and recovered in the host computer as it is shown in this part.

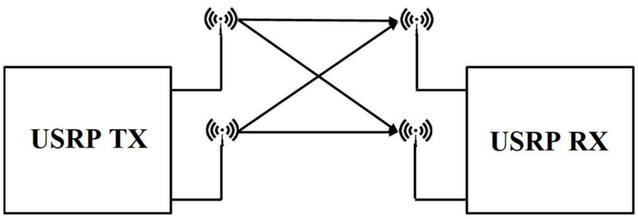

Figure 6. The circuit of USRP MIMO 2×2 antennas

3.1. Universal Software Radio Peripheral (USRP)

USRP is defined as a range of software-defined radios. These software radios allow users to do their experiments with radio waves. USRPs are used by connecting them with host computers through the different speed of links. The software is used to control the hardware in the USRP and transmit or receive data at high-speed links. The USRP B210 hardware works with RF frequencies from 70 MHz to 6 GHz in which it has a Spartan 6 Field Programmable Gate Array (FPGA), and work with USB 3.0 connectivity.

The construction of the USRP platform allows it to work with experiments with a wide range of signals such as FM and TV broadcasting, cellular, Wi-Fi, and so forth. USRP B210 extends the capabilities of B200 by offering more features such as the ability to work with MIMO 2×2, working with a larger FPGA, General Purpose Input/output (GPIO), and it has an external power supply.

The USRP B210 uses an Analog Device RFIC in order to deliver a cost-effective RF experimental platform, and it has the ability to work with 56 MHz of instantaneous bandwidth over a high-bandwidth USB 3.0 connectivity [13].

3.1.1. Transmit blocks

The process of transmission starts when the host computer generates the baseband in-phase (I) and quadrature-phase (Q) signals and sends these signals to the USRP through a USB 3.0 or USB 2.0. Then, the signal needs to be mixed, filtered and interpolated to 64.44 MS/s by the digital up-converter (DUC). The output digital signal is converted to analog by the digital to analog converter (DAC). The output signal is passed through a bandpass filter to mitigate the noise and high-frequency components. The output signal is passed to the mixer in order to up-convert the signal to a user-specified RF frequency. The Phase-Locked Loop (PLL) controls the Voltage-Controlled Oscillator (VCO) in order to make the device clocks and Local Oscillator (LO) will have the ability to be frequency-locked to a reference signal. The final block is the amplifier in which their function is to amplify the signal and transmits it through the antennas [14].

3.1.2. Receiver blocks

The received part starts with the low noise amplifier in which it amplifies the incoming signal. Then the PLL controls the VCO oscillator in order to make the device clocks the LO oscillator can be frequency locked to a reference signal. After that, the mixer down-converts the signals to I/Q components and pass the signal to the band-pass filter to reduce the noise and high-frequency components from the signal. Then the analog-to-digital converter (ADC) digitizes the (I) and (Q) data. The next block is Digital Down-converter (DDC) and their function is to mixes, filters and decimates the signal to a user-specified rate. The last step is to pass the down-converted samples to the host computer by the USB 3.0 or 2.0 connections.

3.2. LTE Transceiver Application Using Polar Codes as a Channel Coding With MIMO

Figure 7 shows the figure of two computers with the two USRP B210 devices. The parameters of USRP that used in the experiment are shown in Table 1.

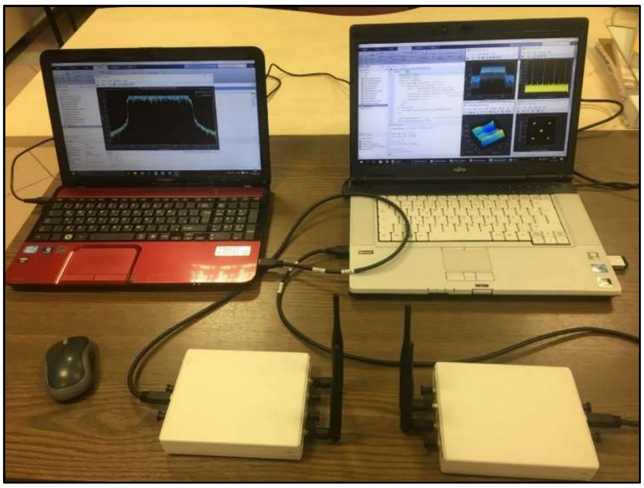

Figure 7. Transmission and reception using two USRP radio devices

The transmission and reception were done by using MIMO 2×2 by using the diversity property in which the data is sent over two antennas to combat the fading and improve the gain of transmission. Moreover, the duplex mode that was used in this transmission is Frequency Division Duplexing (FDD). In the first time, we sent data without adding AWGN as external noise and in the second time, we added noise with SNR is equal to 20dB. We compare between LTE-MIMO system without noise and the same system with AWGN noise in the value of EVM that deals with the accuracy of transmitted symbols within constellation i.e. it measures the quality of signals. In both cases, we were able to recover the transmitted data however the result of EVM was higher with noise and the shape of (I) and (Q) components were not uniform and the antennas were not also uniform in case of adding noise. The following sections explain transmission and reception without noise first then with noise and the comparison between them will be explained as well. In this experiment, we used polar codes as the channel coding scheme and the rate matching polar encoder and the decoder is Successive Cancellation List Decoder with Cyclic Redundancy Check vector (SCL-CRC) that explained in [4].

Table 1. The parameters of the transceiver of USRP radio with LTE-MIMO 2×2

USRP Type	B210
Center Frequency	2.45 GHz
Gain	35 dB
Samples per Frame	19200
Channel Mapping	[1 2]
Master Clock	6×10^6
Interpolation Factor	4
Channel Coding Scheme	Polar Codes
List Size (L)	16
CRC	19

3.2.1. Polar codes implementation in LTE systems with CP-OFDM

In this part, we used LTE systems with polar codes as a channel coding scheme in CP-OFDM waveform type. The parameters used in this transmission are shown in Table 2.

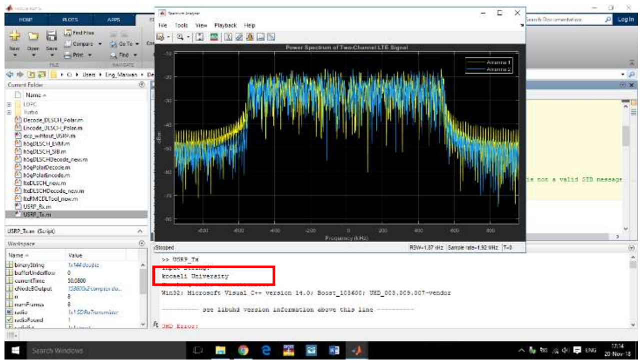

Figure 8. Transmitter spectrum with CP-OFDM and MIMO 2×2

The channels spectrum of the transmitter are shown in Figure 8. Figure 9 shows the reception spectrum of the receiver, constellation diagram, threshold synchronization and channel frequency details. Figure 10 shows MIMO 2×2 antennas channel coefficients. In these figures, we didn't add external noise hence the transmitter spectrum is almost the same of the receiver spectrum. The peak EVM is equal to 21.341dB and the RMS EVM is equal to 8.632dB. The transmitted string is successfully recovered as shown in Figure 9.

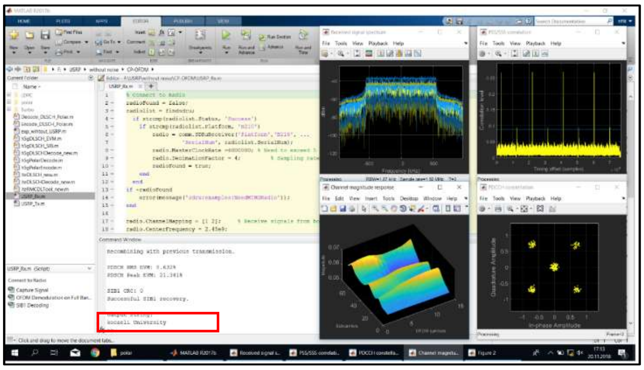

Figure 9. Reception signals with CP-OFDM and MIMO 2×2

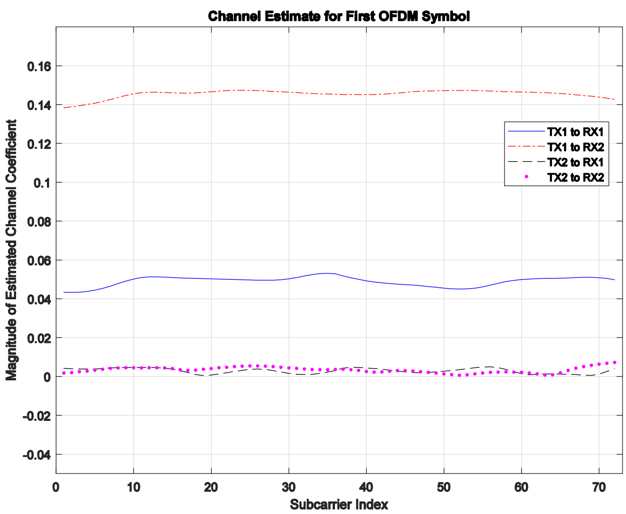

Figure 10. Channel estimation coefficient of MIMO 2×2 and CP-OFDM

Table 2. Configuration of LTE signal with CP-OFDM

Number of resource blocks	6
Cyclic prefix type	Normal
Duplex mode	FDD
Number of cell identity	64
Coding type	QPSK
Transmission Scheme	Transmission diversity
Channel coding scheme	Polar codes
Modulation Type	CP-OFDM
MIMO type	MIMO 2×2

3.2.2. Polar codes implementation in LTE systems with F-OFDM

In this part, we used LTE systems with polar codes as a channel coding scheme in F-OFDM waveform type. The parameters used in this transmission are shown in Table 3. The channels spectrum of the transmitter are shown in Figure 11. Figure 12 shows the reception spectrum of the receiver, constellation diagram, threshold synchronization and channel frequency details. Figure 13 shows MIMO 2×2 antennas channel coefficients. In these figures, we didn't add external noise hence the transmitter spectrum is almost the same of the receiver spectrum. The peak EVM is equal to 59.838dB and the RMS EVM is equal to 9.054dB. The transmitted string is successfully recovered as shown in Figure 12.

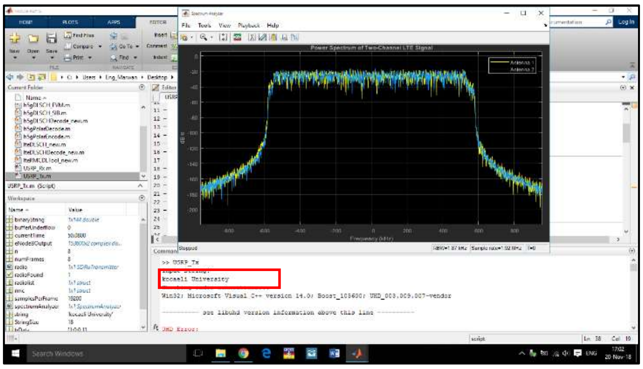

Figure 11. Transmitter spectrum with F-OFDM and MIMO 2×2

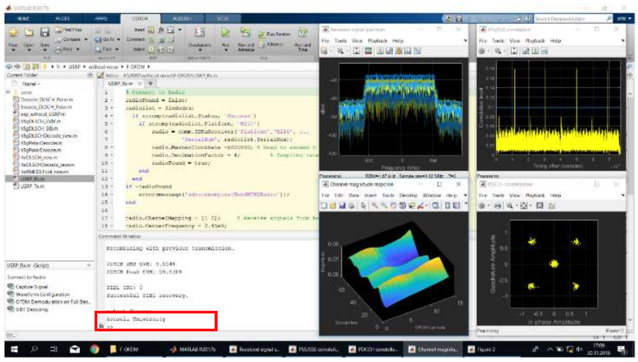

Figure 12. Reception signals with F-OFDM and MIMO 2×2

Table 3. Configuration of LTE signal with F-OFDM

Number of resource blocks	6
Cyclic prefix type	Normal
Duplex mode	FDD
Number of cell identity	64
Coding type	QPSK
Transmission Scheme	Transmission diversity
Channel coding scheme	Polar codes
Modulation Type	F-OFDM
MIMO type	MIMO 2×2

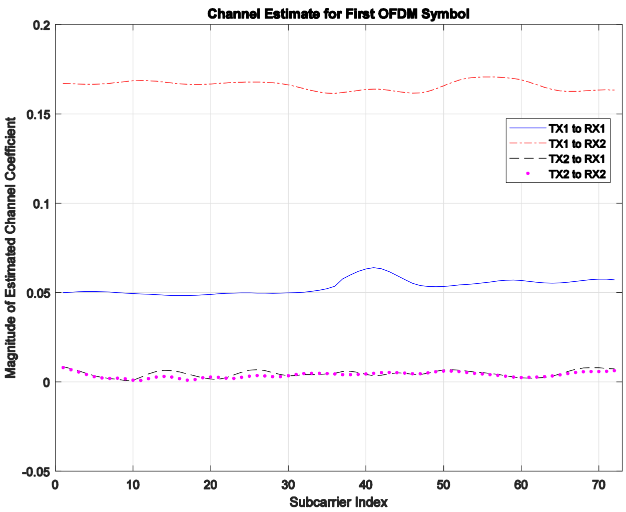

Figure 13. Channel estimation coefficient of MIMO 2×2 and F-OFDM

3.2.3. Polar codes implementation in LTE systems with CP-OFDM and AWGN noise.

In this part, we used LTE systems with polar codes as a channel coding scheme in CP-OFDM waveform type and we added AWGN noise. The parameters used in this transmission are shown in Table 4. The channels spectrum of the transmitter are shown in Figure 8. Figure 14 shows the reception spectrum of the receiver, constellation diagram, threshold synchronization and channel frequency details. Figure 15 shows MIMO 2×2 antennas channel coefficients. In these figures, we added AWGN noise hence the transmitter spectrum is not almost the same of the receiver spectrum. The peak EVM is equal to 135.553dB and the RMS EVM is equal to 60.918dB. The transmitted string is successfully recovered as shown in Figure 14.

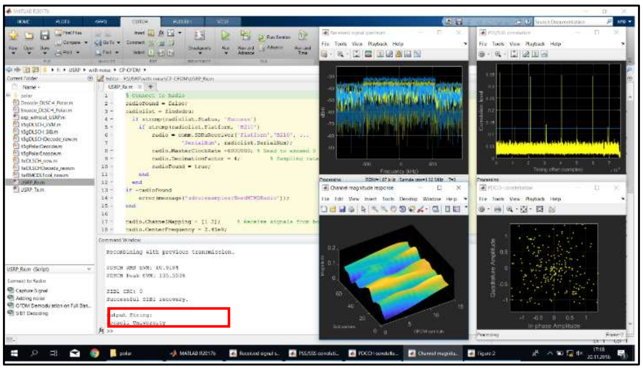

Figure 14. RX signal using MIMO 2×2, CP-OFDM and polar codes with noise

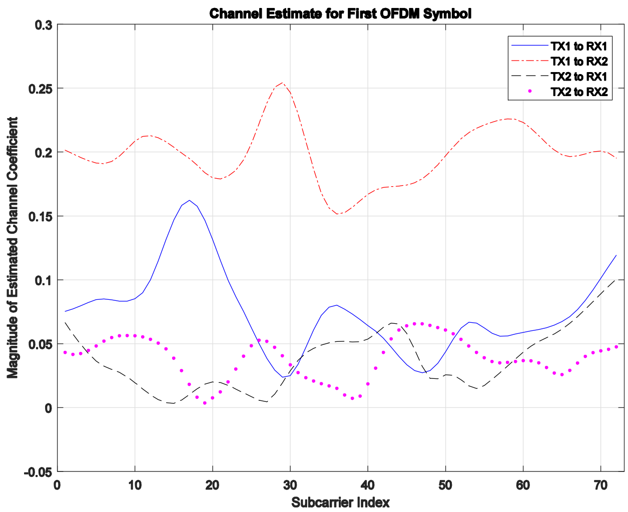

Figure 15. Channel estimation of OFDM symbols

Table 4. Configuration of LTE signal with CP-OFDM

Number of resource blocks	6
Cyclic prefix type	Normal
Duplex mode	FDD
Number of cell identity	64
Coding type	QPSK
Transmission Scheme	Transmission diversity
Channel coding scheme	Polar codes
Modulation Type	CP-OFDM
MIMO type	MIMO 2×2
SNR (for noise)	20 dB

3.2.4. Polar codes implementation in LTE systems with F-OFDM and AWGN noise

In this part, we used LTE systems with polar codes as a channel coding scheme in F-OFDM waveform type and we added AWGN noise. The parameters used in this transmission are shown in Table 5. The channels spectrum of the transmitter are shown in Figure 11. Figure 16 shows the reception spectrum of the receiver, constellation diagram, threshold synchronization and channel frequency details. Figure 17 shows MIMO 2×2 antennas channel coefficients. In these figures, we added AWGN noise hence the transmitter spectrum is not almost the same of the receiver spectrum. The peak EVM is equal to 176.059dB and the RMS EVM is equal to 63.998dB. The transmitted string is successfully recovered as shown in Figure 16.

Table 5. Configuration of LTE signal with F-OFDM

Number of resource blocks	6
Cyclic prefix type	Normal
Duplex mode	FDD
Number of cell identity	64
Coding type	QPSK
Transmission Scheme	Transmission diversity
Channel coding scheme	Polar codes
Modulation Type	F-OFDM
MIMO type	MIMO 2×2
SNR (for noise)	20 dB

Table 6. Comparison between CP-OFDM and F-OFDM

	CP-OFDM	F-OFDM	CP-OFDM	F-OFDM
	(without noise)		(with noise)	
peak EVM (dB)	21.341	59.838	135.55	176.059
RMS EVM (dB)	8.632	9.054	60.918	63.998

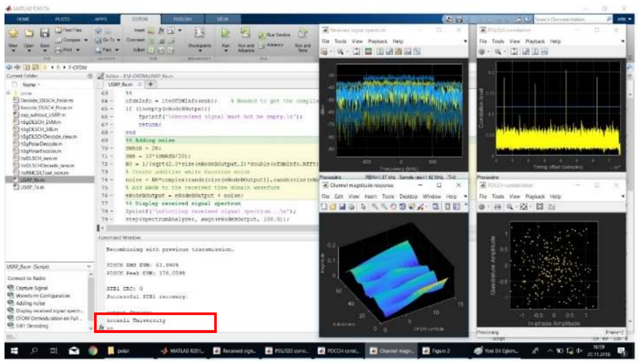

Figure 16. Rx signal using MIMO 2×2, F-OFDM and polar codes with noise

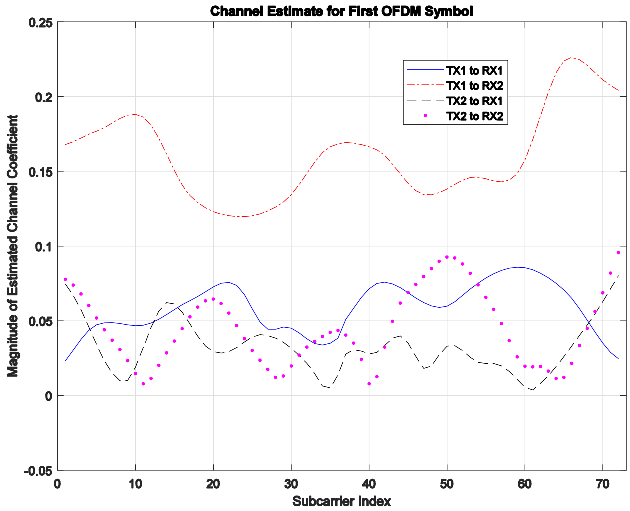

Figure 17. Channel estimation of F-OFDM symbols with noise

4. CONCLUSION

During this study, we studied two different waveforms that are expected to be used in 5G systems. The new coding scheme, polar codes were used in this study to show the transmission and reception process. Firstly, the difference between conventional CP-OFDM and then F-OFDM was presented in details. Then the advantages and disadvantages of using each waveform were mentioned. Although F-OFDM waveform achieves more flexibility than CP-OFDM, it increases the system complexity.

In the practical part of this study, we sent and received data by using LTE-MIMO 2×2 with using polar codes as the channel coding scheme in two USRP radios. A string was sent through one USRP device and successfully received by another USRP device in all cases. Firstly, we did the experiment by sending and receiving the signal without using external noise and left the noise of the environment and successfully received the signal. In the second time, we added AWG noise to the received signal with SNR = 20 dB and successfully received the signal. We used polar codes with rate-match set and SCL-CRC with L = 16.

Table 6 summarizes the result of transmission and reception among the two USRP radio devices. It can be concluded that the EVM value of CP-OFDM is better than that of F-OFDM in both cases (peak and RMS). This means that the accuracy of received symbols in CP-OFDM is better than that received by F-OFDM.

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