A STUDY ON MODULATION TECHNIQUES FOR 5G

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FACULTY OF ENGINEERING
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ABSTRACT

The 5^{th} generation of mobile communication network, or commonly known as 5G, is expected to be deployed sometime around year 2020. Ever since the first generation of mobile communication was deployed in 1980s, the demand of bandwidth has never been enough. In 5G, we are expecting more new devices to be integrated in the network due to the convenient of wireless and mobility to allow the devices easily connected to the internet, anywhere, anytime. These devices include smart devices, sensors, and even machines and vehicles. One way to satisfy the 5G requirements is by enhancing the modulation techniques. In 4G, OFDM is use as the multiplexing technique. OFDM has been known to increase the network capacity tremendously, but it has some drawbacks as well, such as high out-of-band (OOB) emission that requires guard bands among the subcarriers. Consequently, the spectral efficiency decreases. A number of new multicarrier methods such as FBMC, F-OFDM and UFMC have been proposed to overcome OOB emission in OFDM. UFMC seem to be the best potential candidate for 5G. Similar to other methods, UFMC uses digital filter to reduce the OOB emission. Longer filter may reduce OOB emission, but long filter also increases the complexity of the system. In this study, we carry out simulation using Matlab to study the effect of filter length on the network performance. Our study shows that the filter length has no direct relationship corresponding to the performance parameters of BER, FER and throughput. This suggests the selection of filter length required optimization, instead.

ABSTRAK

Rangkaian komunikasi mudah alih generasi ke-5 dijangka akan digunakan sekitar tahun 2020. Sejak pelancaran rangkian komunikasi generasi pertama pada tahun 1980-an, permintaan jalur lebar tidak pernah cukup. Dalam generasi ke-5, di samping telefon bimbit tradisi atau telefon pintar, kami menjangkakan penyepaduan peranti bukan tradisional ke dalam rangkaian. Peranti ini seperti peranti pintar, sensor, dan juga kenderaan. Ini adalah kerana kemudahan tanpa wayar dan mudah alih telah membolehkan peranti mudah dihubungkan ke internet, di mana sahaja, pada bila-bila masa. Generasi semasa, 4G, menggunakan OFDM sebagai pembawa penghantaran udara. OFDM telah dikenali untuk meningkatkan kapasiti dari semua kaedah yang digunakan sebelum ini. Bagaimanapun, OFDM juga mempunyai beberapa kelemahan seperti pelepasan OOB yang tinggi yang menyebabkan sesetengah band pengawal diperlukan. Ini mengurangkan kecekapan spektrum. Bilangan pengangkut pelbagai baru seperti FBMC, F-OFDM dan UFMC telah dicadangkan untuk mengatasi kelemahan OOB yang diperolehi oleh OFDM. UFMC adalah calon berpotensi terbaik untuk digunakan dalam rangkaian 5G. UFMC dan kebanyakan calon berpotensi baru menggunakan penapis digital untuk mengurangkan pelepasan OOB. Penapis lebih panjang boleh mengurangkan OOB yang lagi tinggi tetapi akan meningkatkan kerumitan sistem. Dalam kajian ini, hasil simulasi menggunakan Matlab menunjukkan bahawa panjang penapis tidak mempunyai hubungan langsung yang berkaitan dengan parameter prestasi BER, FER dan kapasiti. Ini mencadangkan bahawa pengoptimuman panjang penapis yang diperlukan.

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Not to forget, my course mate, that we are supported one and other along the way of preparing our own work. At last but not least, to those who supported and helped me in one or other way, thank you.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

1G	:	First generation
2G	:	Second generation
3G	:	Third generation
3GPP	:	The 3rd Generation Partnership Project
4G	:	Fourth generation
5G	:	Fifth generation
BER	:	Bit error rate
BS	:	Base station
CP	:	Cyclic prefix
dB	:	Decibel
eMBB	:	Enhanced-mobile broadband
FBMC	:	Filter bank multi carrier
FDD	:	Frequency division duplex
FDM	:	Frequency division multiplexing
FER	:	Frame error rate
FFT	:	Fast Fourier Transform
FMT	:	Filter multi tone
F-ODFM	:	Filter-orthogonal frequency division multiplexing
Gbps	:	Giga bits per second
GSM	:	Global System for Mobile communications
ICI	:	Inter carrier interference
IFFT	:	Inverse Fast Fourier Transform
IoT	:	Internet of Things
ISI	:	Inter symbol interference

kbps	:	Kilobits per second
LTE	:	Long term evolution
LTE-A	:	LTE advance
M2M	:	Machine to Machine
Mbps	:	Megabits per second
MIMO	:	Multi Input Multi Output
mm	:	Millimetre
mMTC	:	Massive Machine Type Communications
OFDM	:	Orthogonal frequency division multiplexing
OOB	:	Out of band
OQAM	:	Offset QAM
PAPR	:	Peak to average power ratio
PSK	:	Phase shift keying
QAM	:	Quadrature amplitude modulation
SISO	:	Single input single output
SMS	:	short message service
SMT	:	Staggered multi tone
SNR	:	Signal to noise ratio
TUW	:	Institute of Telecommunication of TU Wien
UE	:	User equipment
UFMC	:	Universal filter multi carrier
URLLC	:	Ultra-Reliable Low Latency Communications
ZP	:	Zero padding

CHAPTER 1: INTRODUCTION

We have seen the evolution of mobile communication drastically in its technology, infrastructure and application since its first deployment for commercial use more than 30 years ago. The first generation (1G) of mobile communication focuses on voice call. Its successor, second generation (2G) or commonly known as GSM (Global System for Mobile communications) has introduced more features to the mobile services, including SMS (short message service) and security. SMS allows cellphone to send text messages on top of making voice call. In other words, we have seen both voice and data services in 2G. Since then, the focus is very much on the data transmission in mobile network. Therefore, we have seen the third generation (3G) networks allow data rate up to 2 Mbps for web browsing and data application. Next, the fourth generation (4G) or known as LTE-A has seen an all data network, in which both the voice and data services are supported by packet-switched network and a much higher data rate is achieved. In summary, we have seen the data rate increases from 2.4 kbps in 1G system (Hayat, Sanae, & Ahmed, 2017) to a peak downlink data rate of 100 Mbps in the 4G. This is over 40 thousand fold. Two factors contributed to this growth of data rate: more advanced user equipment and modulation technique that offers higher data rate.

The fifth generation (5G) of mobile network is expected to be deployed around year 2020 (Rupendra & Dharma, 2015). Although the standard has yet to be finalized, 5G is expected to have capacity between 10-50 Gbps (Akhil & Rakesh 2015). Based on the previous trend and expectation, higher data rate is one of the key improvements in 5G. Besides, billions of devices are expected to be connected to the network. More importantly, these devices may not be only smartphones. The future of 5G is expected to provide smart living by integrating sensor networks, machine-to-machine (M2M) communication, vehicular ad hoc network (Rupendra & Dharma, 2015). Hence, the overall focuses of 5G is higher throughput, lower latency, higher reliability, energy efficiency and scalability. 4G has improved the data rate and increased the capacity for mobile communication and the 5G will is expected to be main factor for achieving IoT (Zaidi et al., 2018). In 5G, we expect three main types of services. They are enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), and massive Machine Type Communications (mMTC) (Popovski, Trillingsgaard , Simeone, & Durisi, 2018). mMTC and URLLC are generally the two main streams of IoT. mMTC is refer to massive numbers of devices, low cost devices and able to have 10 years or more years of life expectancy. Sensor nodes and smart metering are example of mMTC devices. Sensor nodes can either be field sensors or body sensors. URLLC, as the name suggests, it is use for reliable and low latency devices. Example of URLLC is the communication between smart grid, public safety, remote surgery, industry automation control, vehicular and any devices that has no room for delay (Aankarali, Pekoz, & Arslan, 2017). While eMBB is the continuous of the 4G internet broadband service (Popovski et al., 2018).

These 3 types of services have their own expectation. The attention of eMBB in 5G is basically higher peak data rate. The URLLC required low latency of communication, while mMTC type of service required small data payload. Unlike to previous generation, 5G is expecting different kind of services in the same network. To cater these services, review on the currently multiplexing or modulation technique becomes important.

1.1 Problem statement

Let us review the current system. OFDM is currently used in 4G mobile wireless communication system as the modulation technique. The OFDM method used in 4G is CP-OFDM. In this writing, OFDM is refer to CP-OFDM, unless otherwise specified. OFDM is the digital multicarrier system. It is made up by several individual carriers. Each carrier is modulated using conventional modulation scheme such as QAM. The carriers are orthogonal to each other and allow neighboring channel to be closely place without interference. Hence, this helps to increase the spectral efficiency as compared to the conventional FDM. In OFDM, each carrier has smaller bandwidth. The advantage of using smaller bandwidth of carrier in OFDM is overcome the narrow band interference and selective fading. However, OFDM has the drawback of high side lobe, and high PAPR (Xianru, Wei, & Yixin, 2016). High PAPR reduces the energy efficiency of the radio transmitter(Grigory , Valery , Altay , & Bolat 2017). This requires the transmitter to consume more energy and especially bad for mobile devices that run on battery. OFDM also experiences higher side lobe that causes lower spectral efficiency. In the current LTE, 10% of the spectrum is used as guard band to prevent the OOB emission. With this is mind, there is a need to look at the possibility of improving OFDM to be use in 5G network.

Several newly proposed multicarrier has been study to improve the OFDM to suit the 5G requirements. Among them are FBMC, F-OFDM and UFMC. From the summary of the study of Ijza et al, UFMC is proven to be the best candidate in terms of reducing OOB emission and PAPR, and is suitable for short burst data as compared to OFDM and other potential methods (Ijaz, Zhang, Xiao, & Tafazolli, 2016). To reduce the OOB emission, we can perform either windowing or filtering (Venkatesan & Valenzuela, 2016). Most of the newly propose multicarrier candidates are using digital filter to reduce the OOB emission. However, as pointed out by Zhang et al, the proper sub-band filter design is required and filter length can change the performance of the system differently (Zhang, Ijaz, Xiao, Imran, & Tafazolli, 2016).

1.2 Objectives

The aims of this study is to study the performance of new potential 5G carrier multiplexing technique. UFMC is chosen due to its better overall performance as compared to other potential methods. We set the following two objectives for this project:

1. To compare on the network performance under various filter lengths.
2. To analyze the performance of UFMC at different sizes of carrier per sub-band.

1.3 Organization

This report is divided into 5 chapters. This current chapter is to briefly introduce the next generation of mobile network and problem. In chapter 2, we will go through the OFDM and newly proposed multicarrier FBMC, F-OFDM and UFMC. Chapter 3 is the research methodology. This chapter explain the software being use and the selection on parameters. Chapter 4 presents the results collected and the observation. Conclusion and some possible future work is presented in chapter 5.

CHAPTER 2: LITERATURE REVIEW

Due to some drawback of ODFM in current 4G and the suitability of the use of OFDM in 5G's application, new waveforms or carriers are being actively propose, study and research. Nevertheless, of disadvantages of OFDM, multicarrier is the trend in the upcoming 5G or future generation of mobile communication. Almost all proposal of new waveforms are multicarrier. In this chapter, we will briefly look into OFDM, FBMC, F-OFDM and UFMC.

FBMC is multicarrier system similar to OFDM. Each carrier is filtered in FBMC (Grigory et al., 2017). FBMC is actively study by research group such as METIS, EMPhhAtiC (Rupendra & Dharma, 2015). F-OFDM, or filter-OFDM, is utilizing the OFDM with sub-band filtering. (Xi , Ming, Lei, Jianglei , & Jing 2015). UFMC is sub-band filtering similar to FBMC. Each sub-band is consisting number of carriers.

2.1 OFDM-Orthogonal Frequency Division Multiplexing.

Despite some of the draw back might see in OFDM in 5G application, the understanding of OFDM still important. Many new multicarrier is develop based on OFDM. The history of OFDM is back to 1960s. It was proposed by Chang and Saltzberg (Aankarali et al., 2017).

OFDM is make up of multiple small bandwidth of carrier, instead of single carrier by itself. This individual carrier is known as sub carrier. All the sub carrier is orthogonal to each other. The IFFT in the OFDM is to transform the frequency signal to time and FFT is for the reverse. OFDM uses IFFT and FFT, which allow the both the transmitter and receiver reduce it complexity. CP insertion in OFDM is to make OFDM resist against the delay spread in the channel. OFDM also known to be easily extend to the use of MIMO.

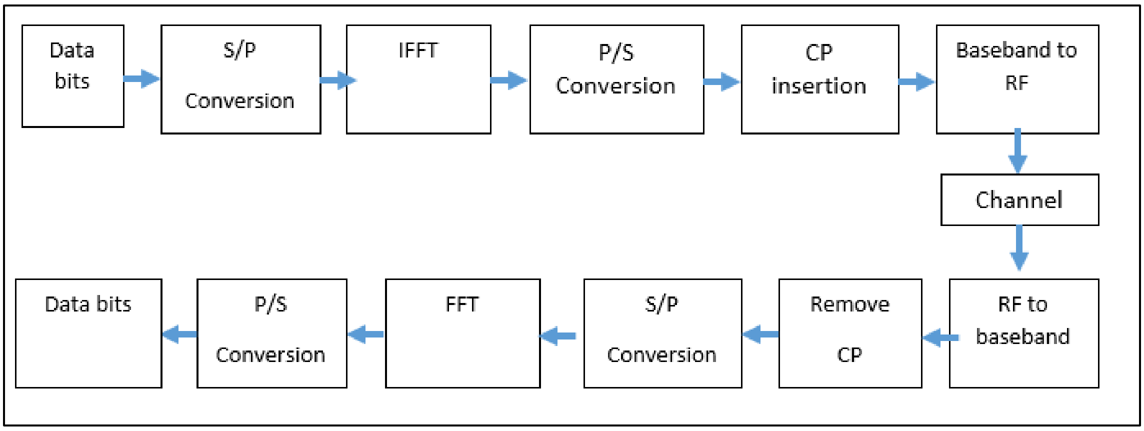

Figure 2.1: Block diagram for OFDM (Gerzaguet, Ktenas, Cassiau, & Dore, 2016).

2.2 FBMC-Filter Bank Multi Carrier

FBMC is proposed as a new multicarrier to overcome the shortfall that may encounter by OFDM in the future wireless communication system (Nissel, Schwarz, & Rupp, 2017). Each carrier in FBMC is filtered and it is able to provide strength to counter ICI. In OFDM, it uses one filter to filter all its all subcarriers at once. FBMC employ one filter for each individual carrier instead. The advantage of doing this is able to reduce the out of band emission (Kishore, Umar, & Naveen, 2017). FBMC generally have 2 main stream, namely FBMC/OQAM and FMT (filter multi toned). Filter multi tone is based on the QAM while FBMC/OQAM is based on Offset QAM (Hayat et al., 2017). FBMC/OQAM is also known as SMT (staggered multi tone). SMT is said to exhibit better spectral efficiency when compare to FMT (Schaich & Wild, 2014).

Investigation on FBMC is carry out at test bed using center frequency of 2.5 GHz and 60 GHz by Nissel et al using the variant of FBMC/OQAM. The real world result shown that the FBMC at 2.5 GHz has better throughput than OFDM at higher SNR. The throughput is higher for FBMC than OFDM when the SNR is larger than 0dB. At low SNR, 0dB and below, the throughput of FBMC is comparable to the throughputs of OFDM (Nissel et al., 2017). FBMC also known to be the best in suppressing the OOB emission when compare to other multicarrier such as f-OFDM and UFMC (Zhang, Ijaz, Xiao, Molu, & Tafazolli, 2018). This also consistent with the work done by Xi and his team (Xi et al., 2015).

But, FBMC's filter length is multiple time of sample per multicarrier symbols, which make the entire system much complicated (Pooja , Silki , & Himanshu, 2018). This will also cause long ramp up and ramp down, this is not suitable for bursty data.

Aside the complexity in the filter, the FBMC also increase the computational difficulty, since each filter are applied to each carrier.

Although FBMC still is better than OFDM in many expect such as OOB emission, however, FBMC overall is complicated to implement. This could be the factor FMBC will not employ in 5G by 3GPP (Stefan Pratschner et al., 2018).

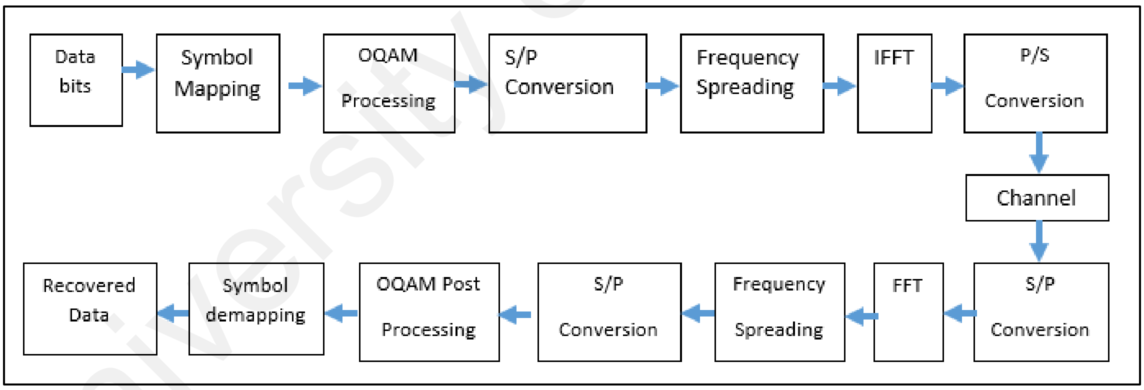

Figure 2.2: Block diagram for FMBC (Hayat et al., 2017).

2.3 Filter-OFDM

Filter OFDM or f-OFDM is similar to the OFDM. In the f-OFDM, the total carriers are divided to number of sub-band and each sub-band is then filtered. Each of the sub-band can have different carrier spacing. The objective to have different carrier spacing at different sub-band is to ensemble the need of type of services. Therefore, the f-OFDM can have different carrier spacing, different CP length, different FFT/IFFT points at different sub-band (Abdoli, Jia, & Ma, 2016). In f-OFDM, filter is applied at both receiver and transmitter. The signal of all the sub-bands are then sum and modulated by PSK or QAM for transmission. F-OFDM are able to reduce the OOB emission about 2%. The OFDM in current 4G LTE use 10% as the guard band due to the OOB (Zhang et al., 2018). The reduction in OOB, of course will increase the spectrum efficiency.

However, same like other multicarrier, f-OFDM also has some drawback. Pointed out by Zhang et al, each sub band needed individual of FFT, the complexity will increase as the number of sub band increased (Zhang et al., 2018). This is foresee become a problem for the low cost IoT devices, that may not support such complexity. Multi rate f-OFDM is proposed in their work as a solution to this problem.

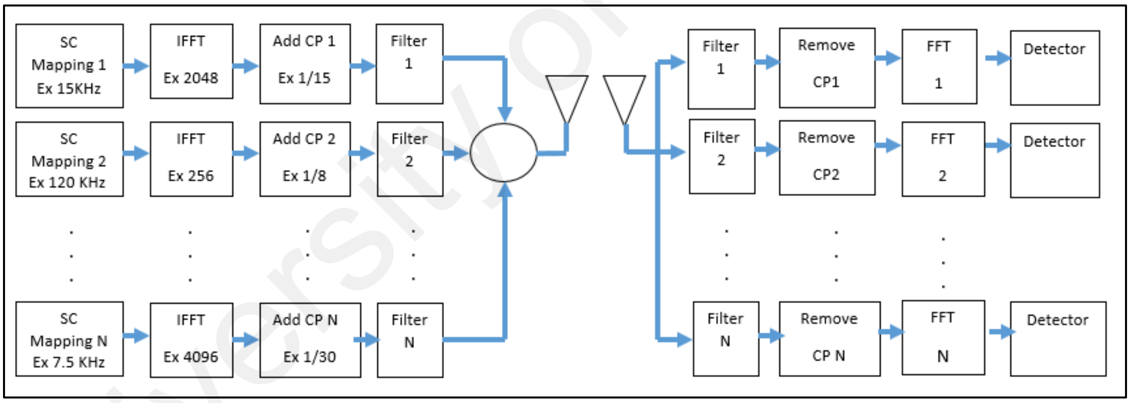

Figure 2.3: Block diagram for F-ODFM (Xi et al., 2015).

2.4 UFMC- Universal Filter Multi Carrier

Another sub-band filter type of multicarrier is UFMC. UFMC is similar to FMBC, instead of filter each carrier in FBMC, UFMC filter at sub-band level. Similar to f-OFDM, UFMC is divide the entire bandwidth to several sub-band. In UFMC, CP is an option (Hayat et al., 2017). The use of CP in UFMC is to improve the ISI similar to OFDM. The application of filter will help to reduce the OOB emission, this is similar to the f-OFDM. UFMC also known as generalization multicarrier of FBMC and f-OFDM (Rani & Rani, 2016). Similar to f-OFDM, UFMC also can use with different spacing of carrier in different sub-band (Schaich & Wild, 2014).

The advantage of the UFMC is the reduce in the filter length when compare to FBMC, since the sub band is filter instead of individual carrier. The signal is filter with band filter which having the filter length, L, after N point of IFFT. At the receiver side, the UFMC performs 2N point FFT on the receiving data.

In the simulation work done by Rani et al, the PAPR of UFMC is reducing as the QAM increase in the mapping technique. When compare to OFDM, PAPR of UFMC is better than the PAPR of OFDM at 16 QAM, 64 QAM and 256QAM. But the PAPR of UFMC is poorer than PAPR of OFDM at 4 QAM. They also show that UFMC has a better OOB emission compare to OFDM using Matlab simulation. Both the UFMC and OFDM are having 200 subcarriers. However, the UFMC are having 10 sub-band with 20 carrier per sub-band instead of 200 subcarriers per block in OFDM (Rani & Rani, 2016).

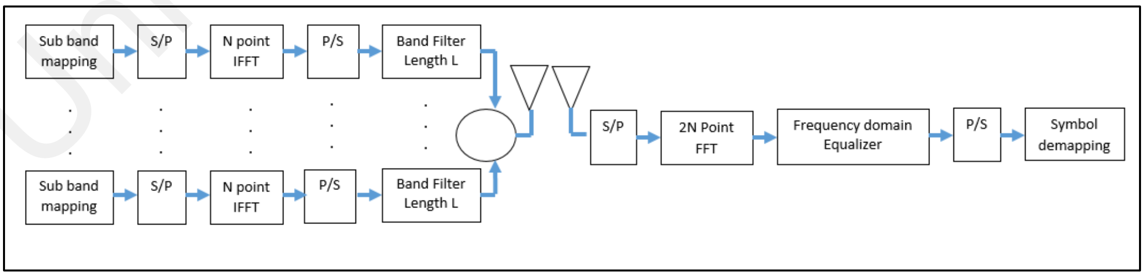

Figure 2.4: Block diagram for UFMC (Hayat et al., 2017).

CHAPTER 3: RESEACH METHODOLOGY

In this study, investigation is done using software simulation to understand the performance of UFMC under different filter lengths and different sizes of carrier per sub-band.

3.1 Vienna 5G link level simulator

The simulation study was carried out using Vienna 5G link level simulator developed by the Institute of Telecommunication of TU Wien. The 5G simulator is a script written using the Matlab. Some parameters are required to be set before the simulation can take place. Currently, this link level simulator supports FDD mode only. Since the scope of the investigation in this work is on the effect of filter length in the UFMC, the simulation is done with SISO system. This is done by setting the number of antenna to 1 at both the user and base station. The center of the carrier frequency is set to 2.5 GHz. The script power delay model is based on the low GHz spectrum, which is not suitable to study or investigate the mmWave region.

In general, two base stations are setup and each base station has only one UE. Two links are established: UE1-BS1 and UE2-BS2, which means UE1 is only receiving signal from BS1 and UE2 is only receiving signal from BS2. The two UEs are set to not interfere with each other by setting the topology attenuation to a large value (100 in this case). The topology is shown in Figure 3.1. The two BSs are set to use OFDM with identical setting for fair comparison. To have better repeatability of the simulation result, the frame size is set to 5000. Setting frame size to 5000, would allow the result is same like running multiple times and the average value is calculated. Other parameters such as equalizer type, channel coding, channel decoding, decoding iteration, user velocity, doppler effect and power profile delay are using the default value in the generic scenario provided in the simulator. The summary of parameters used in the simulation can refer to Table 3.1. Figure 3.2 to Figure 3.4 are example of simulation results.

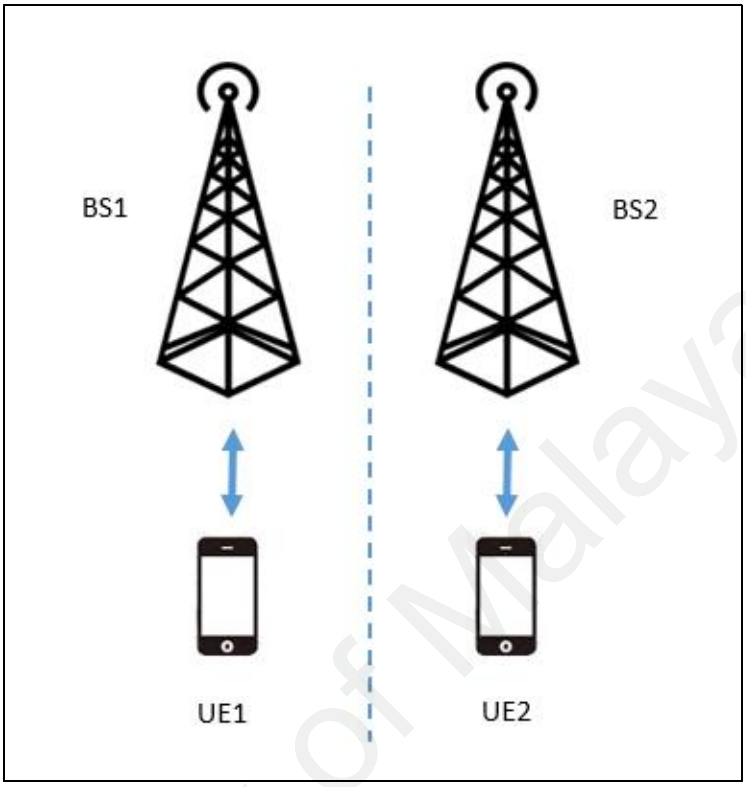

Figure 3.1: UE1 is connected to BS1 and UE2 is connected to BS2. The link UE1-BS1 will not interfere with the link UE2-BS2.

Table 3.1: General parameters setting for simulation using the Vienna 5G link level simulator.

Parameter	Setting value
Frames	5000
txPowerUser (dBm)	10
txPowerBaseStation (dBm)	30
AntennasUser	1
AntennasBaseStation	1
CenterFrequency	2.5e9 (2.5 GHz)
EqualizerType	One-tap
Channel coding	Turbo code
Channel decoding	MAX-Log-MAP
Decoding iteration	8
User velocity	0
dopplerModel	Discrete-Jakes
powerDelayProfile	PedestrianA

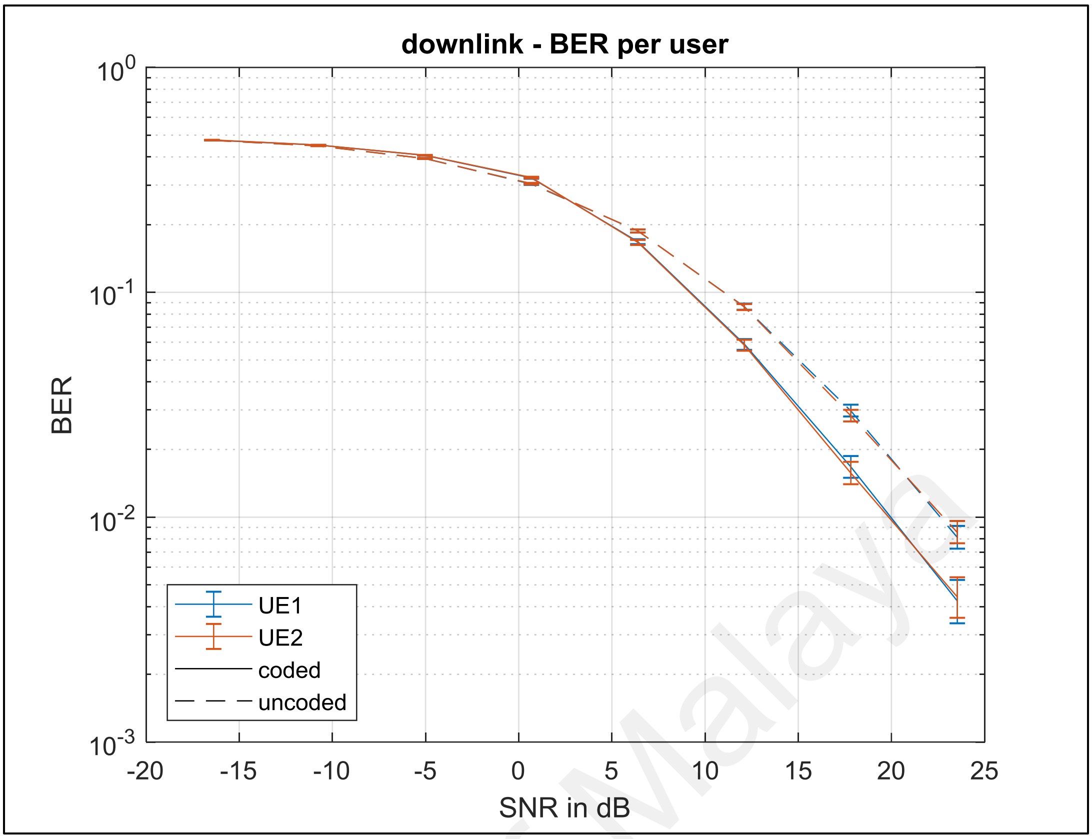

Figure 3.2: Comparison of BER for the two UEs that are using same waveform of OFDM from the respective base station.

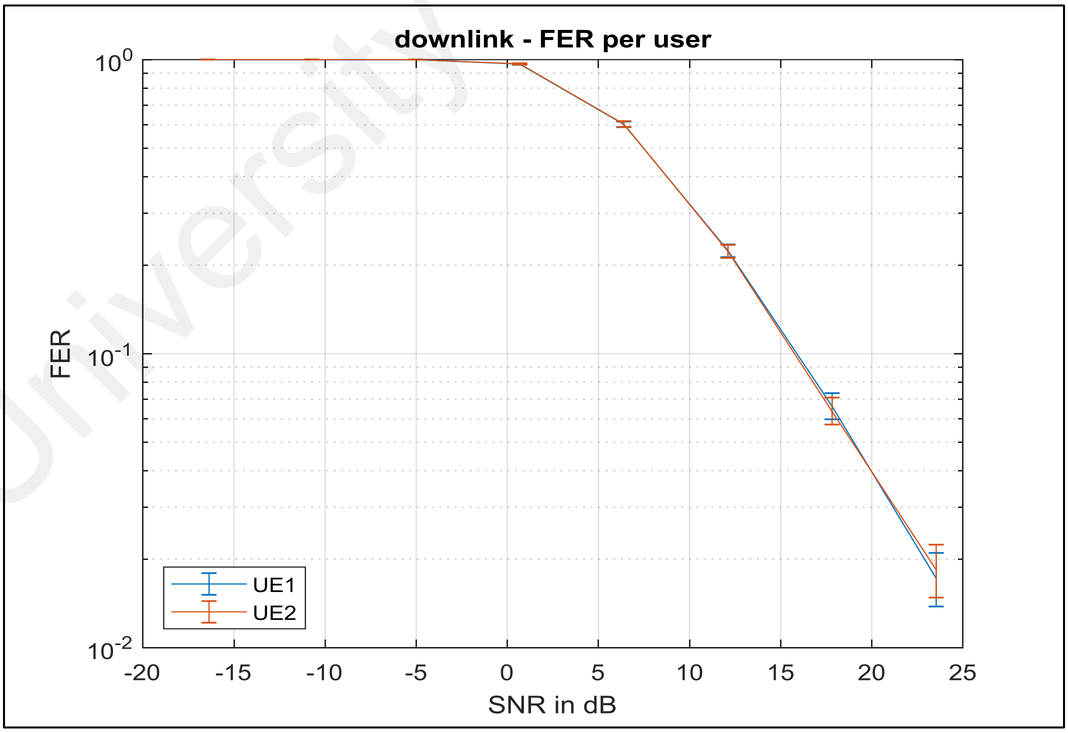

Figure 3.3: Comparison of FER for the two UEs that are using same waveform of OFDM from the respective base station.

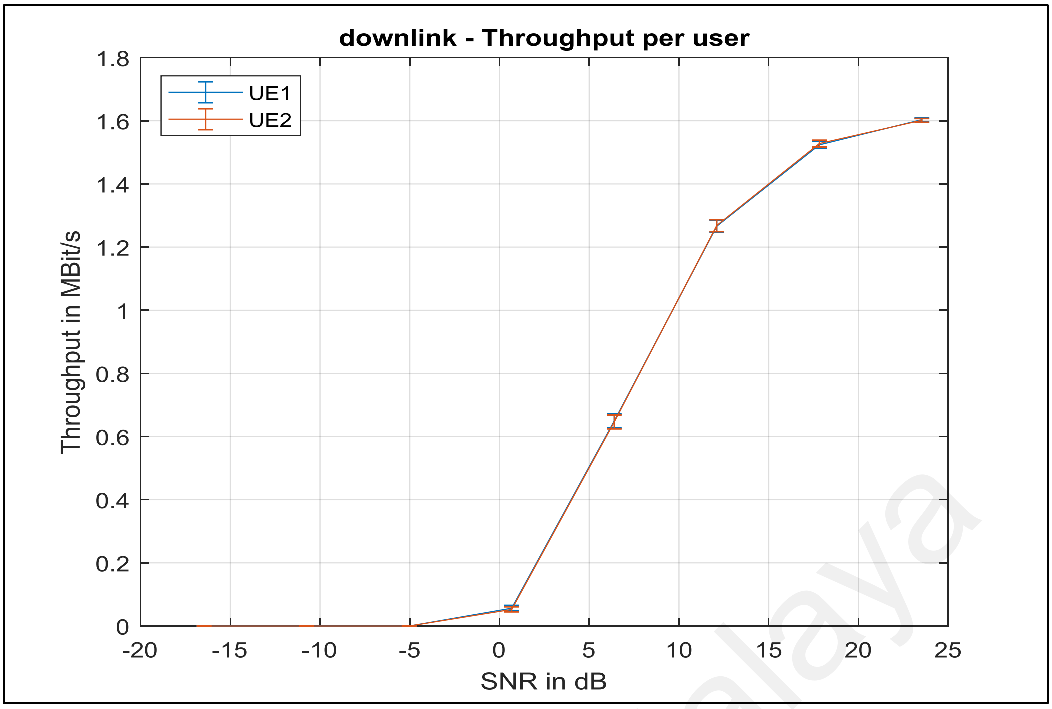

Figure 3.4: Comparison of throughput for the two UEs that are using same waveform of OFDM from the respective base station.

3.2 Topology and setup

In the Figure 3.1, the objective is to select the frame size. In this study, we only need one BS and one UE. The total carrier for BS is always set to 72, which is the value used in the current 4G LTE-A system. The BS is set to UFMC and in each simulation it is set to different carrier per sub-band. The number of carrier per sub-band that been selected are 72, 36, 18, 9 and 1. These values are chosen in such a way that can divisible by 72. This allow us to have 1, 2, 4 ,8 and 72 sub-band respectively.

3.3 Performance Parameters

Three parameters are used to evaluate the network performance, they are throughput, BER and FER.

3.3.1 Throughput

Throughput is the measure of the data successfully transmitted from one point to another point in a given period of time. The data can be measure in bit or byte. In this work, we use bits as the unit for data. The time unit is in seconds. In this work, the throughput is measure the successful data transfer from BS to the UE.

3.3.2 BER- Bit Error Rate

The BER is the ratio of error bits over the total transmitted bits. It is measure the quality of the transmission between two points. Higher BER mean more error occur during the transmission between the two points. Higher BER often due to noisy channel, interference and multipath fading. Lower BER is always preferred. For BER, it consists of both coded and uncoded results. Coded BER is the result of BER based on the channel coding. In this work, Turbo code is use as the channel coding. Turbo code is the default setting in the simulation script. Turbo code also the channel coding use by current 4G LTE-A. Uncoded BER is where no channel coding is being used.

$$BER = \frac{Number\ of\ error\ bits}{total\ transmitted\ bits}$$

3.3.3 FER-Frame Error Rate

FER is the ratio of error frame over total transmitted frames. In FER, when one or more bits is error in a frame, the frame is counted as error frame. It is important to note that FER may not directly correlated BER. Scenario with higher BER may achieve lower FER if the error bits mostly occur in a few particular frames over the total transmitted frames. In our study, we see some high BER with low FER. The throughput is counted the successful transmitted frame(s).

CHAPTER 4: RESULTS AND DISCUSSION

As discussed in Chapter 3, the simulation was done using the Matlab and the performance parameters are Throughput, BER and FER across 16 SNR points. The first section of this chapter presents the throughput of different filter lengths at a specific number of carriers per sub-band in UFMC. Comparison is also done for BER and FER in the second part of this chapter. Other than the number of carriers per sub-band, filter length and ZP (Zero padding), other parameters used in the simulation are given in Table 3.1. The value of ZP is set to L-1, where the L is the filter length (Stefan Pratschner et al., 2017). The minimum filter length is 1. In all simulations, the filter length of UFMC is set to 1 to 60 at a step of 5.

4.1 Throughput

This study is done by comparing the throughput, BER and FER between OFDM and UFMC and between UFMC at different number of carriers per sub-band. Simulation for OFDM with 1 symbol of CP and zero CP OFDM are recorded as benchmark. OFDM with 1 symbol CP is currently use in 4G LTE-A. Since UFMC is this work is without CP, zero CP OFDM is also recorded for fair comparison.

From Figure 4.1, for UFMC with 72 carriers per sub-band, it can be noticed that the throughput of UFMC is generally higher than the OFDM with 1 symbol of CP at all filter lengths. This is consistent with the fact that 1 symbol is redundant in OFDM to fight against delay spread. For UFMC 72 carriers per sub-band, based on the simulation result, except L=1 and L=5, all filter length has better throughput profile when compare to zero CP-OFDM across all SNR. At L=1 and L=5, the UFMC has the same throughput profile to OFDM with zero CP.

When comparing UFMC at different filter lengths, filter length of L=60 gives the highest throughput at lowest SNR, followed by L=50. It can also be observed that for SNR below -13.74 dB, the throughput already achieved maximum for L=60 and L=50. Obviously, this shows that the filter lengths do have impact on the network performance.

In the Figure 4.2, UFMC is set to 36 carriers per sub-band with the total of 72 carriers per BS. Similar to 72 carriers per sub-band, L=50 and L=60 is best filter length when compare the throughput with other filter length at lower SNR in 36 carriers per sub-band. The worse filter length occurs when L=1 and L=5. At filter length of L=20, L=15 and L=25, all these are having lower throughput than OFDM between the SNR -0.4dB to 23.6dB. This result shows that UFMC may perform worse than OFDM.

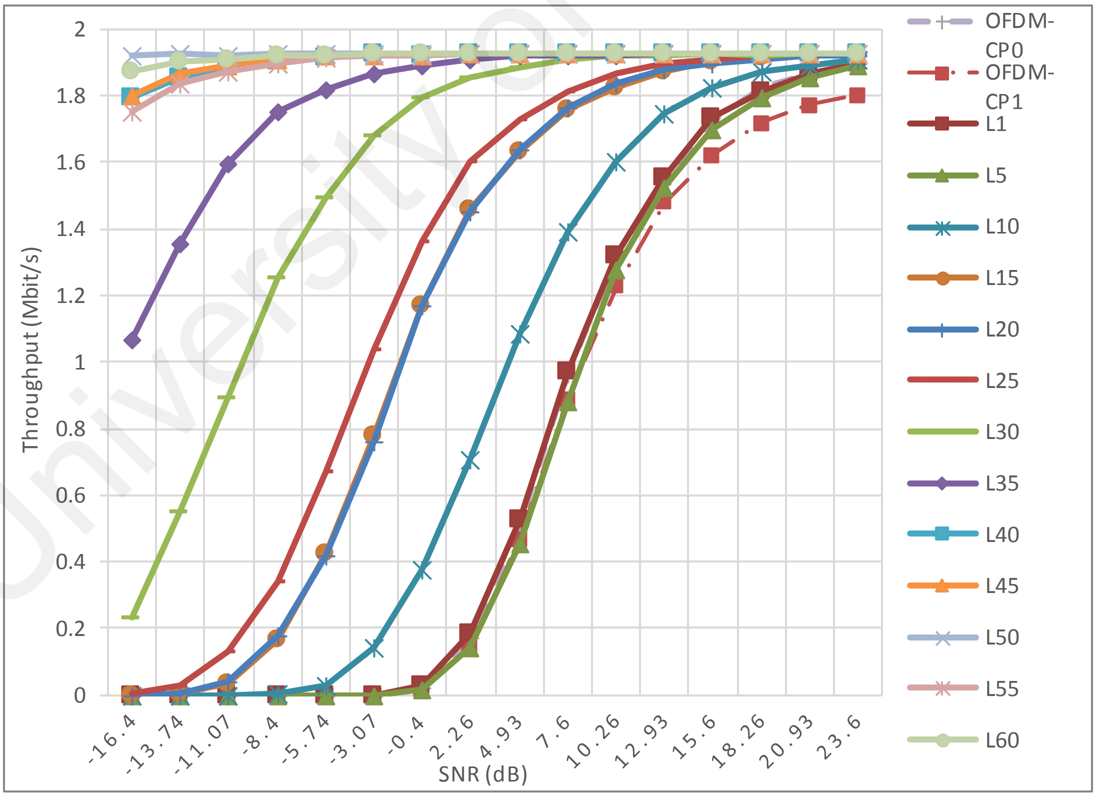

Figure 4.1: Throughput versus SNR at different filter length of UFMC with 72 carriers per sub-band.

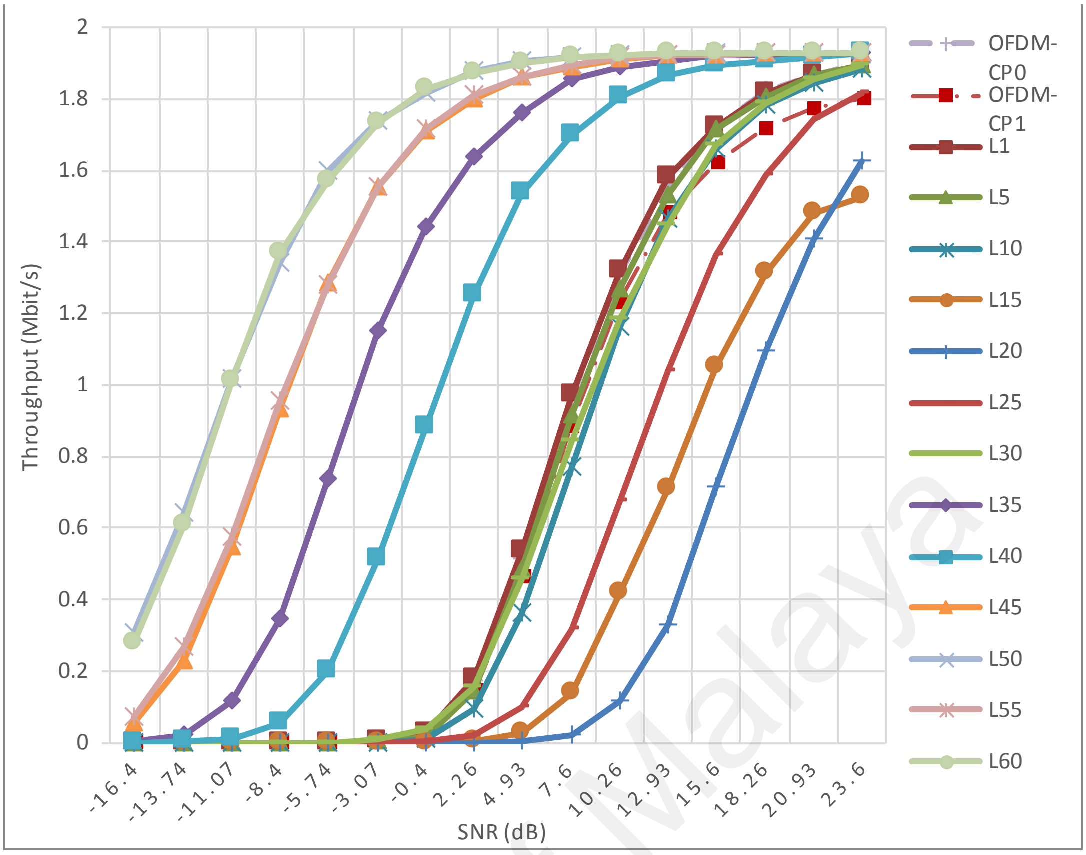

Figure 4.2: Throughput versus SNR at different filter length of UFMC with 36 carriers per sub-band.

Figure 4.3 shows the result of the different filter length for the 18 carriers per sub-band for UFMC. The total carrier of the BS is still 72. Hence the maximum throughput is the same for 72, 36 or 18 carriers per sub-band. When UFMC is set to 18 carriers per sub-band it has the best throughput at lower SNR when L=35. The next best is L=45 and L=60. From the top three highest throughput performance, it suggests that the lower filter length could have the best throughput at lower SNR. But, from the result for all simulated filter length, the best throughput is not happened when filter length L=1, since 1 is the lowest filter length been used. The worse filter length is when L=30. From the figure, at any SNR greater than 10.26 dB, L=30 has the lowest throughput and is obvious that other filter length has better throughput. Hence the filter length has no direct relationship with the throughput performance.

In the Figure 4.4 is the result for UFMC with 9 carriers per sub-band. In this figure, almost all the filter length that tested has the poorer throughput compare to the zero CP-OFDM between the SNR of -0.4 dB to 23.6 dB. Only filter length L=1 is having same throughput profile when compare to zero CP-OFDM. This result shows that, filter has a negative impact at lower carrier per sub-band in UFMC.

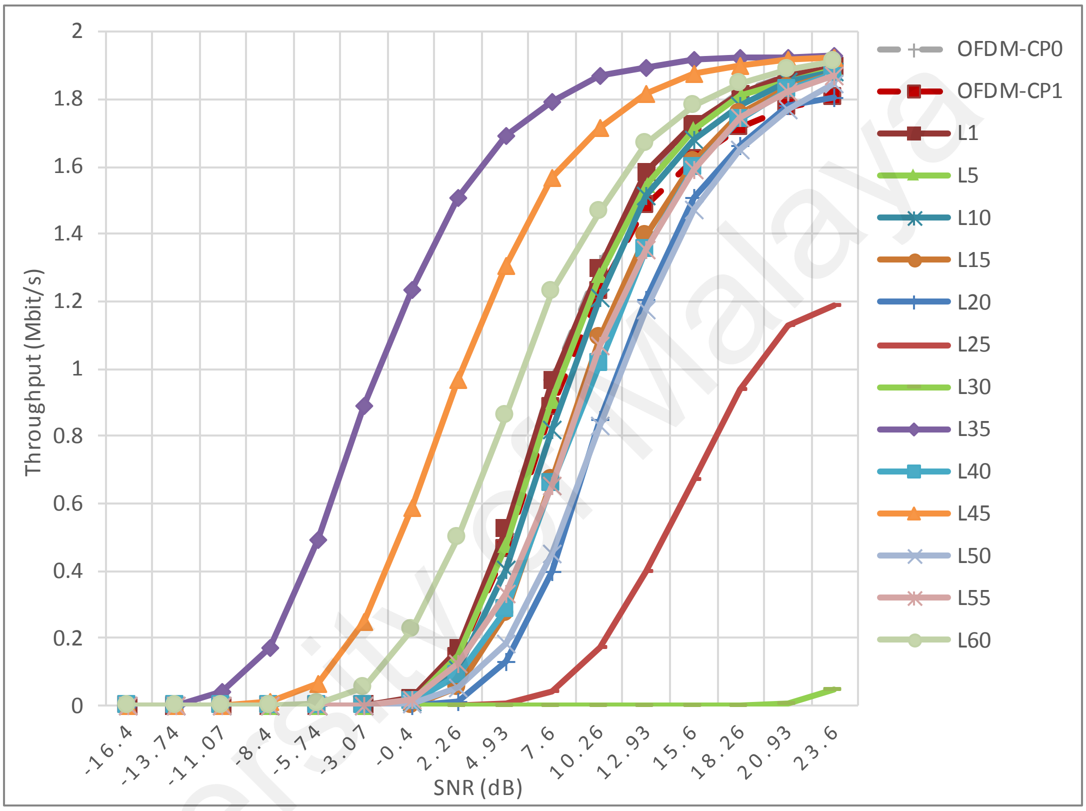

Figure 4.3: Throughput versus SNR at different filter length of UFMC with 18 carriers per sub-band.

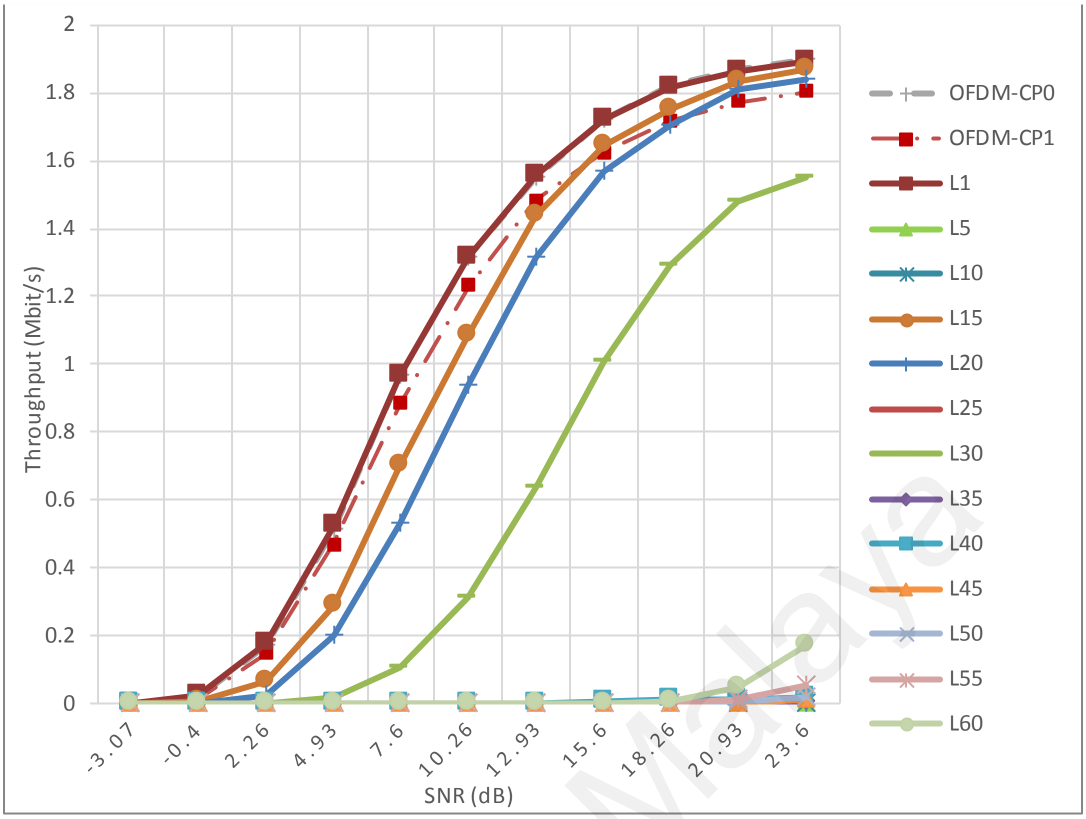

Figure 4.4: Throughput versus SNR at different filter length of UFMC with 9 carriers per sub-band.

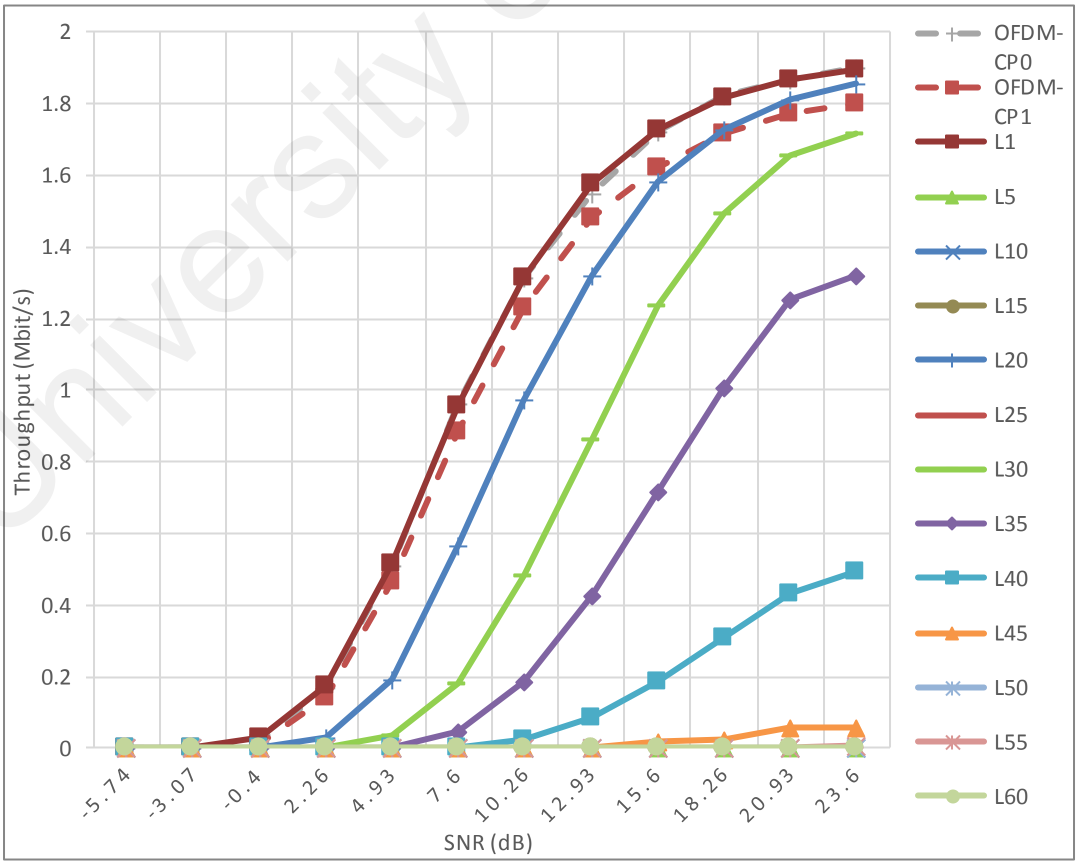

Figure 4.5: Throughput versus SNR at different filter length of UFMC with 1 carrier per sub-band.

When UFMC is set to 1 carrier per sub-band with total 72 carriers in the BS, we can observe that, other than L=1, all the filter length has poorer throughput performance compare to OFDM across the SNR between -0.4 dB to 23.6 dB. When L=1, at 1 carrier per sub-band of UFMC, it has exactly the same profile of throughput of the zero CP OFDM across all the simulated SNR. From Figure 4.1 to Figure 4.5, we can notice that, as the number of carrier decease in a sub-band in UFMC, number of filter length that has a poorer throughput is getting more. Also, as the number of carrier per sub-band decrease, smaller filter length will give better or same throughput when compare to OFDM. These two observations show that the necessary of filter or necessary of lower carrier per sub-band to implement in UFMC.

Previously the comparison is done with number of carrier per sub-band with the change of filter length L. In this section, result is compare with the fixed filter length with the change of number of carrier per sub-band. From Figure 4.6 to Figure 4.12 is the plot for L=1, 10 and step of 10 until 60.

When filter length in UFMC is L=1, the throughput is having same profile across all SNR for any carrier per sub-band. At this filter length, the throughput is slightly better than OFDM with 1 symbol CP across higher SNR.

From Figure 4.6 to Figure 4.12, we can observe the trend that as the filter length increase, the throughput performance is getting poorer for smaller carrier per sub-band in UFMC.

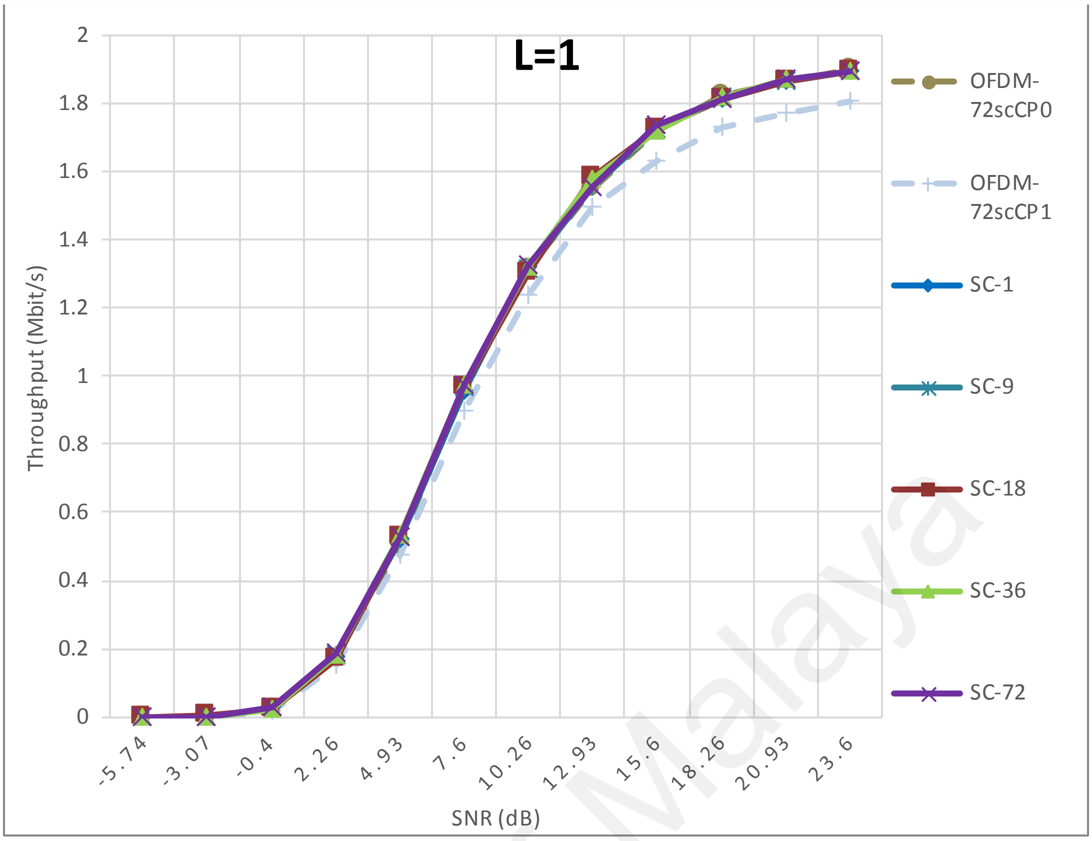

Figure 4.6: Throughput versus SNR for UFMC at different number of carrier per sub-band with filter length 1.

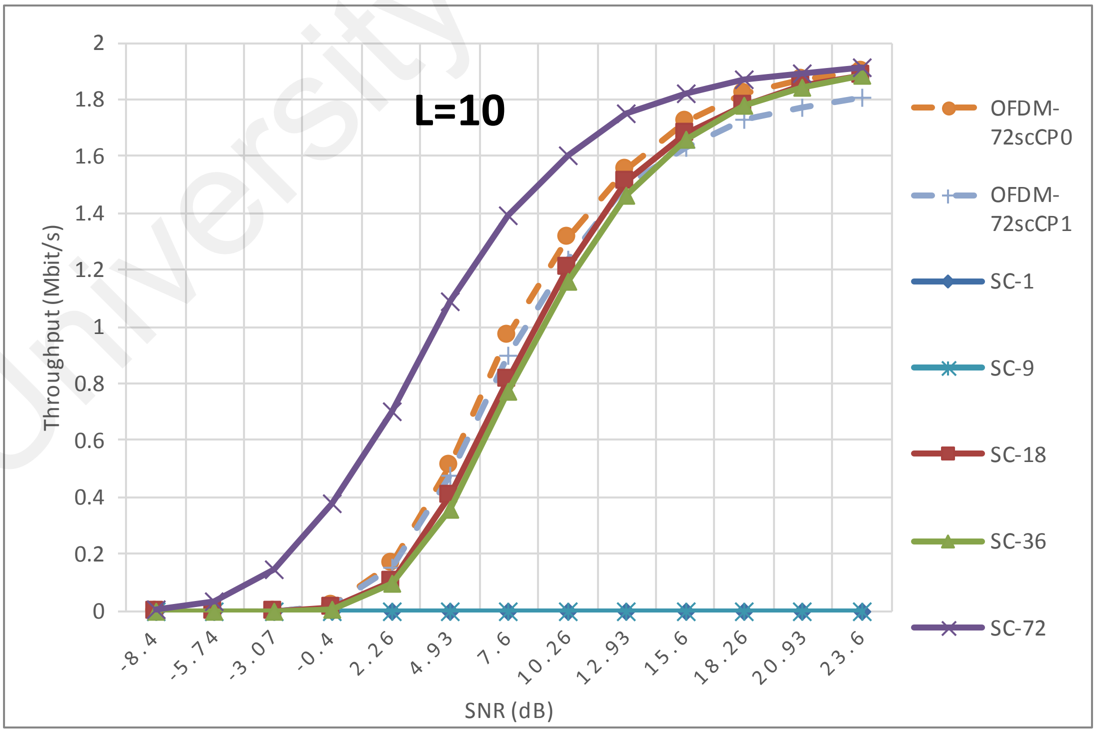

Figure 4.7: Throughput versus SNR for UFMC at different number of carrier per sub-band with filter length 10.

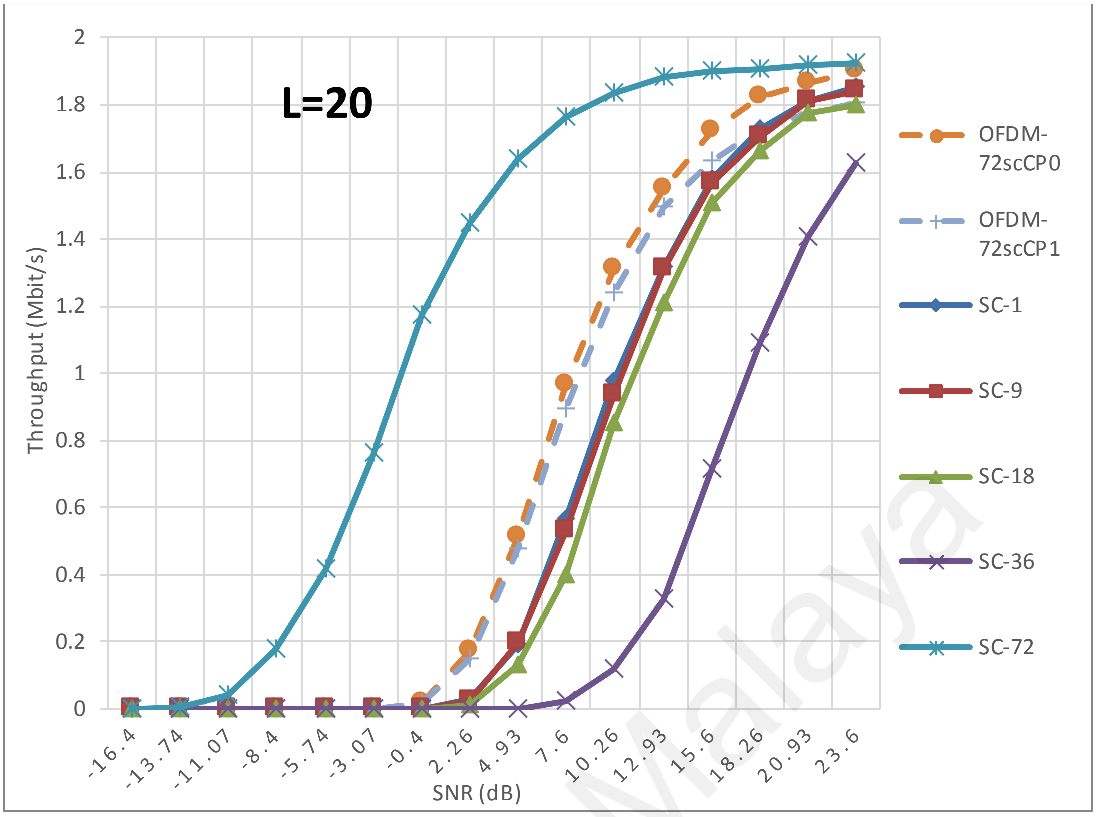

Figure 4.8: Throughput versus SNR for UFMC at different number of carrier per sub-band with filter length 20.

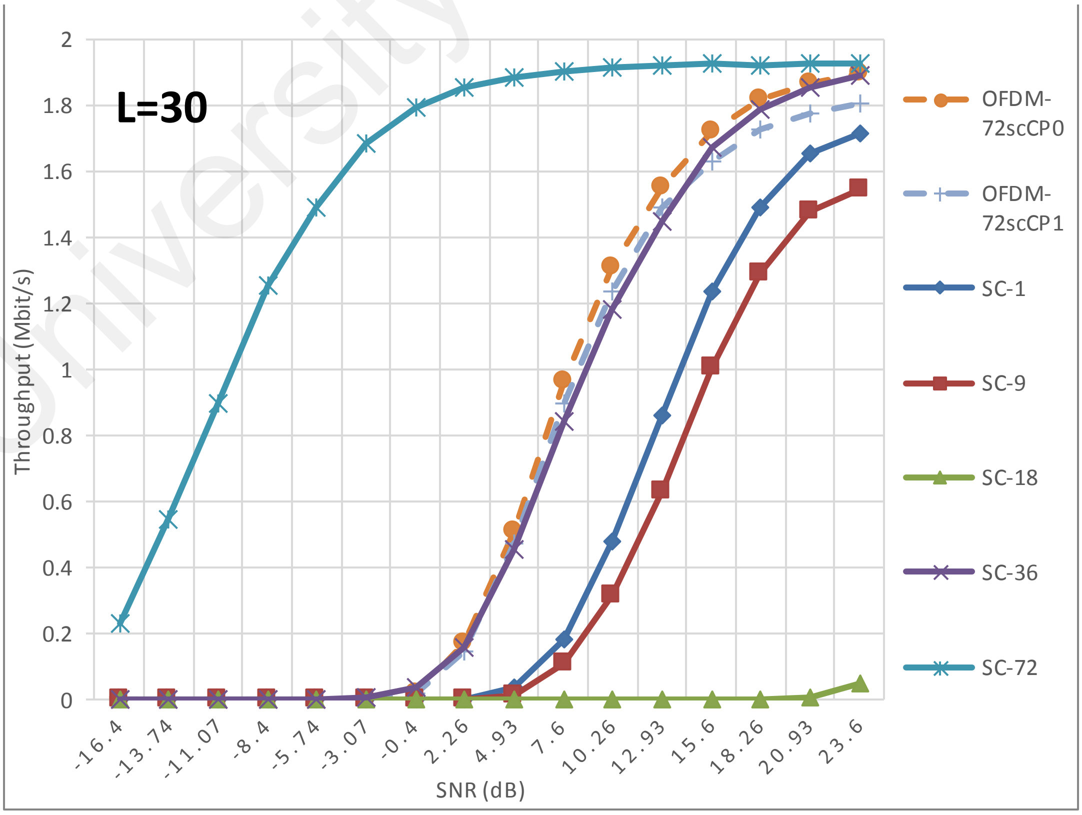

Figure 4.9: Throughput versus SNR for UFMC at different number of carrier per sub-band with filter length 30.

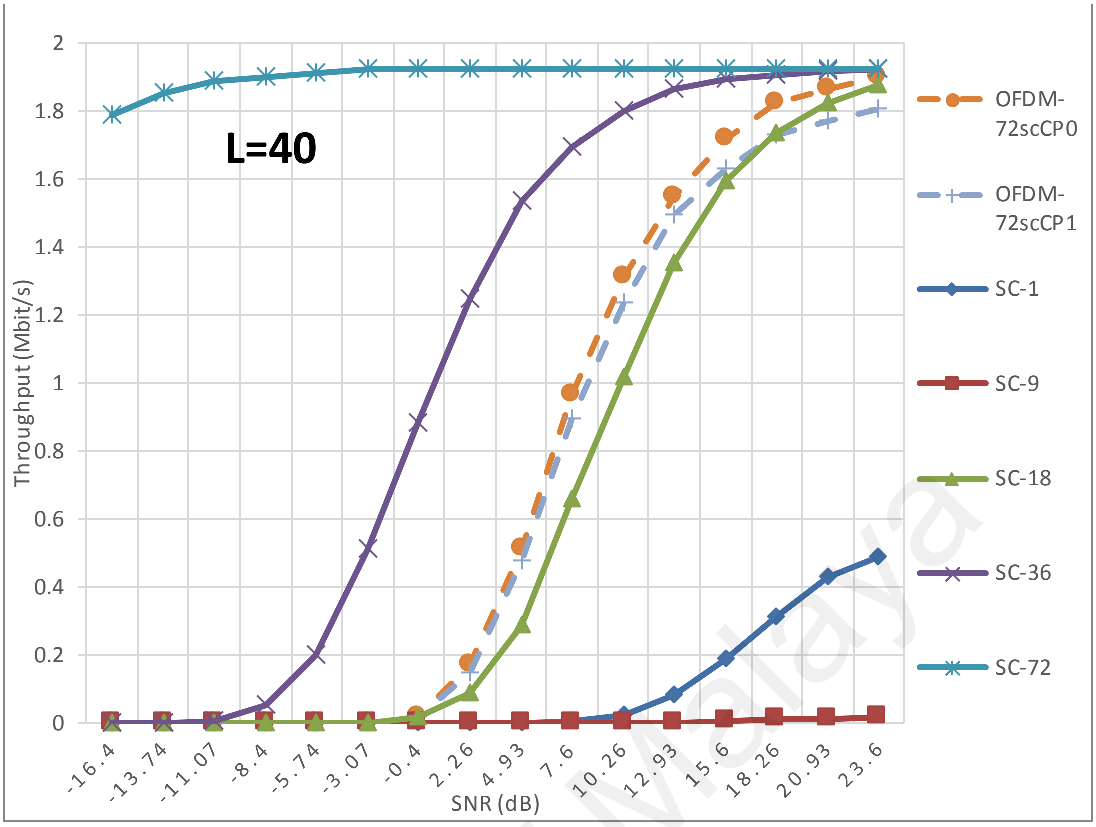

Figure 4.10: Throughput versus SNR for UFMC at different number of carrier per sub-band with filter length 40.

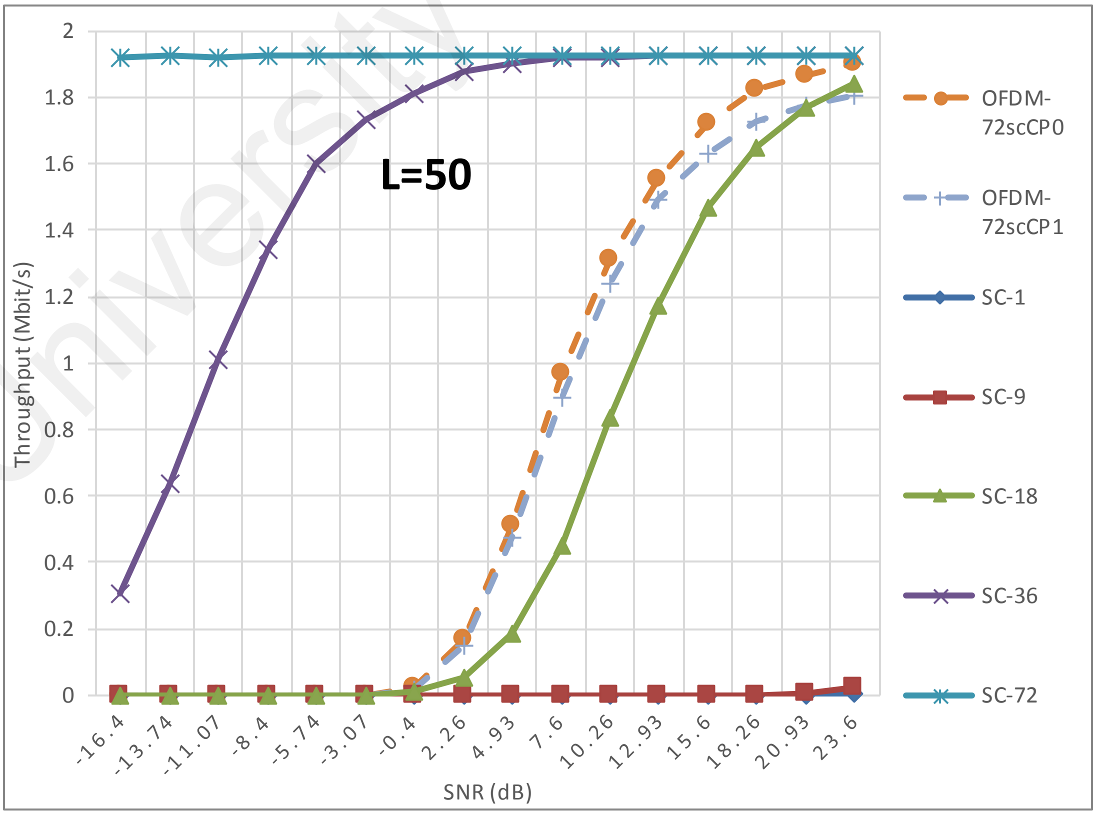

Figure 4.11: Throughput versus SNR for UFMC at different number of carrier per sub-band with filter length 50.

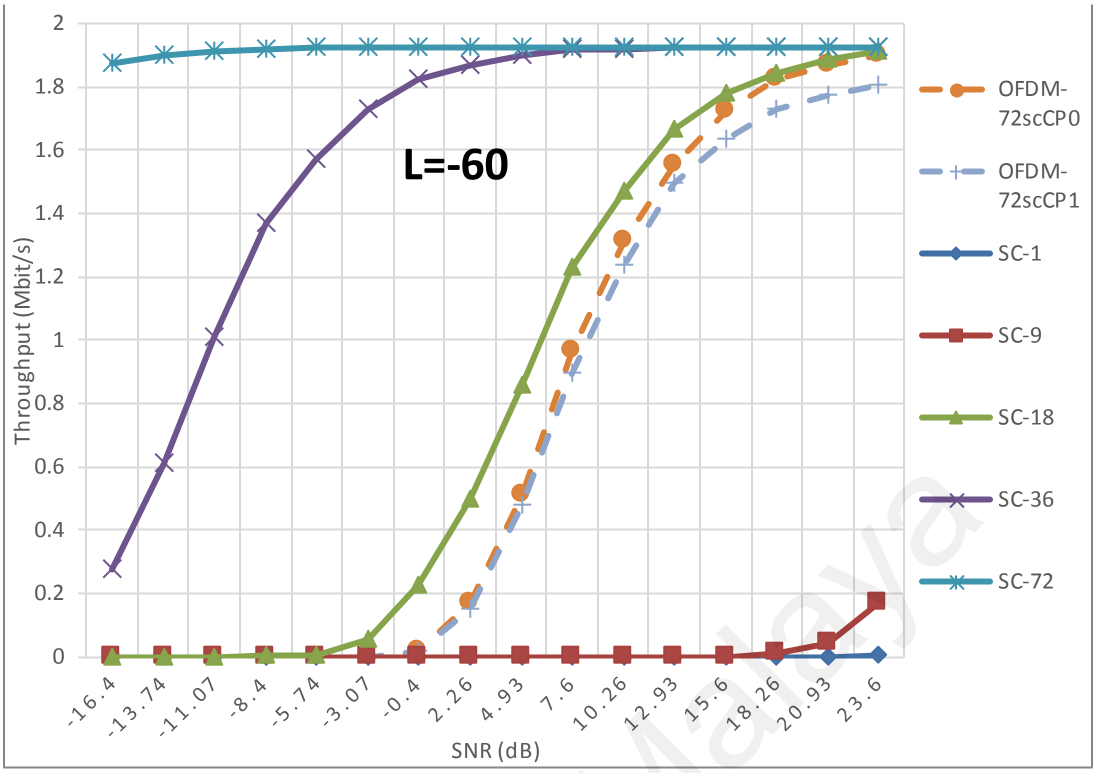

Figure 4.12: Throughput versus SNR for UFMC at different number of carrier per sub-band with filter length 60.

4.2 BER and FER

In Figure 4.13 and Figure 4.14, UFMC with 72 carriers per sub-band, both coded and uncoded result having same BER profile when compare to OFDM at the filter length of L=1. Other than L=1, the BER profile shown that all UFMC has poorer performance compare to OFDM across all the simulated SNR. In Figure 4.13, the second best BER profile is when filter length L=25. Best BER is refer to low BER at low SNR. Uncoded result also shows L=25 is the second best BER in Figure 4.14. The worse BER profile for UFMC is at filter length L=45 and L=55 at 72 carriers per sub-band. We are try to find the relationship between L and BER. From the observation, the best is when L=1, the second best is L=25 and the worse is at L=45 and L=55. Since L=5 is not the second best, and L=60 is not the worse, it shows that filter length is not directly impacting the BER.

When we look into the FER as shown in Figure 4.15, the best FER profile is when L=50 and L=60. It suggests that most the BER occur in the same frames. Similar to throughput and BER, the length of L has no distinct relationship when correlate to FER.

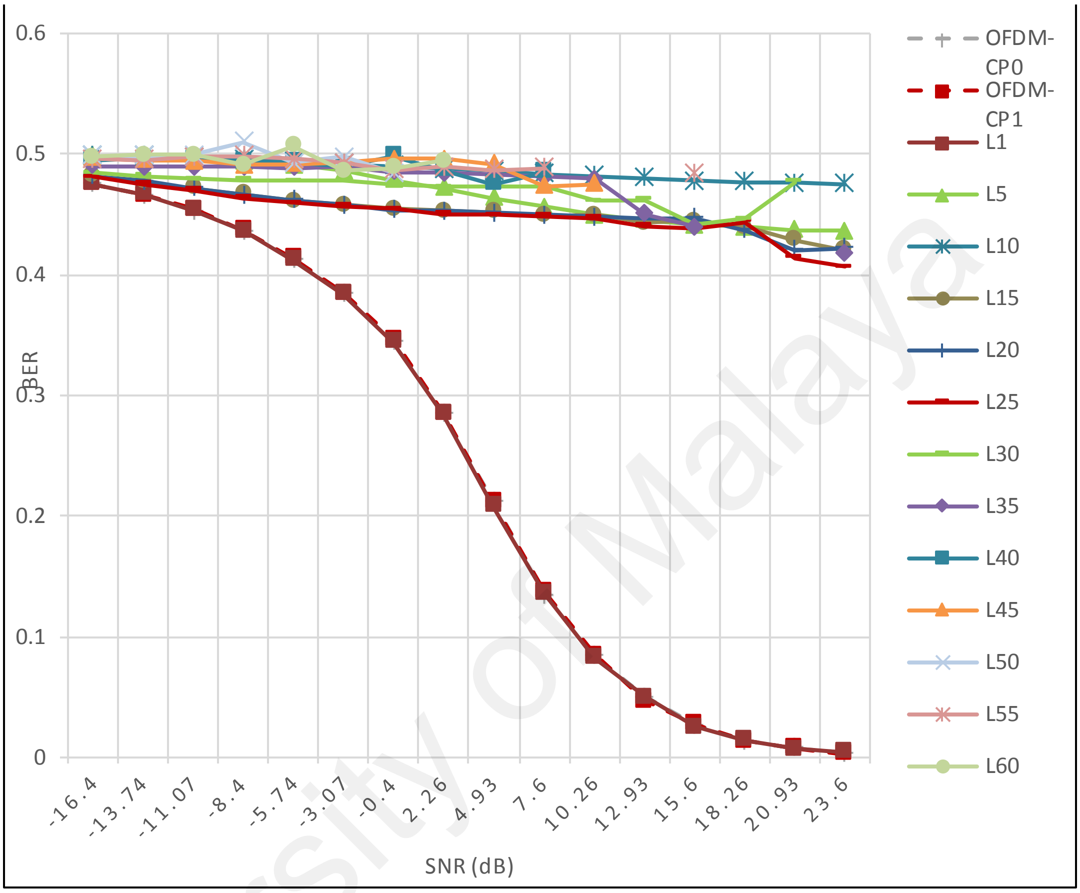

Figure 4.13: BER (coded) versus SNR for UFMC at different filter length with 72 carriers per sub-band.

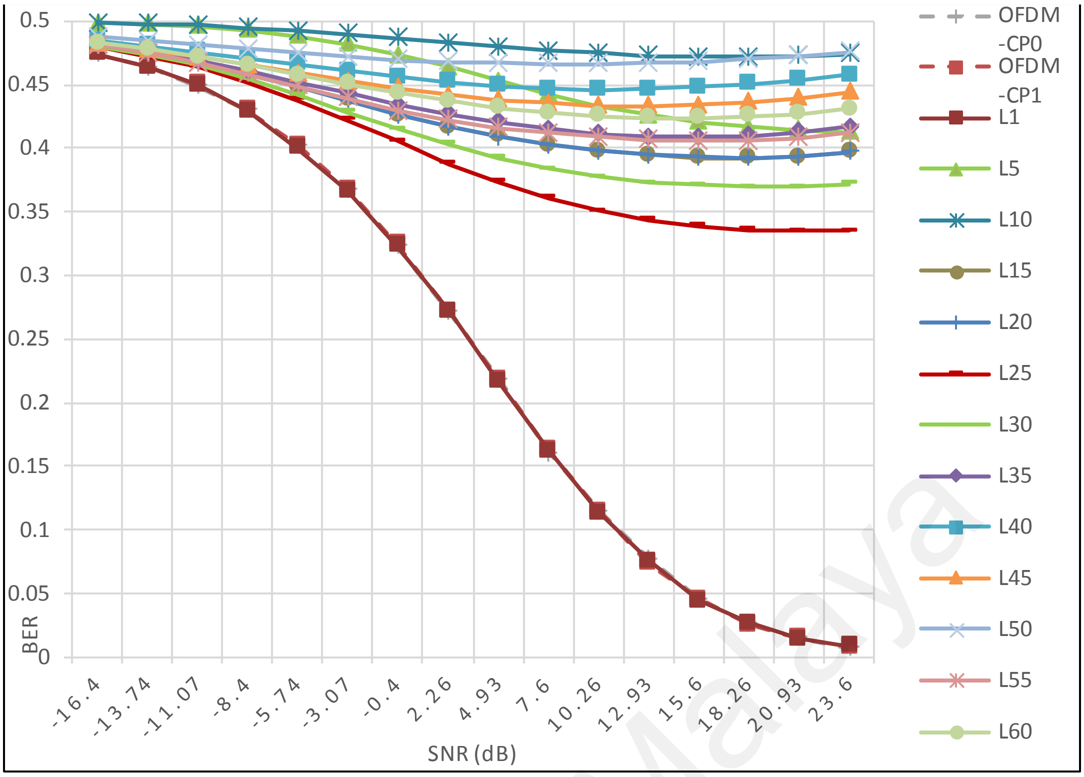

Figure 4.14: BER (uncoded) versus SNR for UFMC at different filter length with 72 carriers per sub-band.

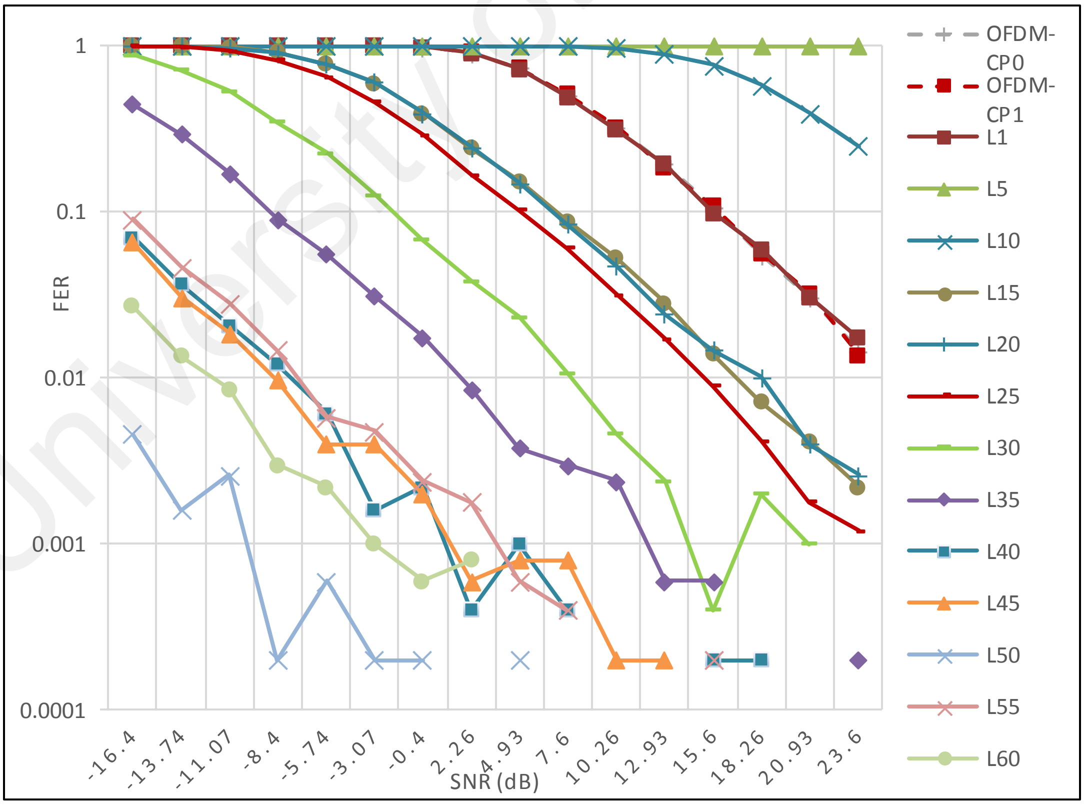

Figure 4.15: FER versus SNR for UFMC at different filter length with 72 carriers per sub-band.

In the 36 carriers per sub-band scenario, the best BER profile is when L=1, 5, 10 and 15. The worse BER profile when L=50, 45 and 35. If we check on the FER, the best FER is when L=60 and L=50. This result is same as 72 carriers per sub-band. When L=1, 72 carriers or 36 carriers per sub-band has a same FER profile when compare to OFDM.

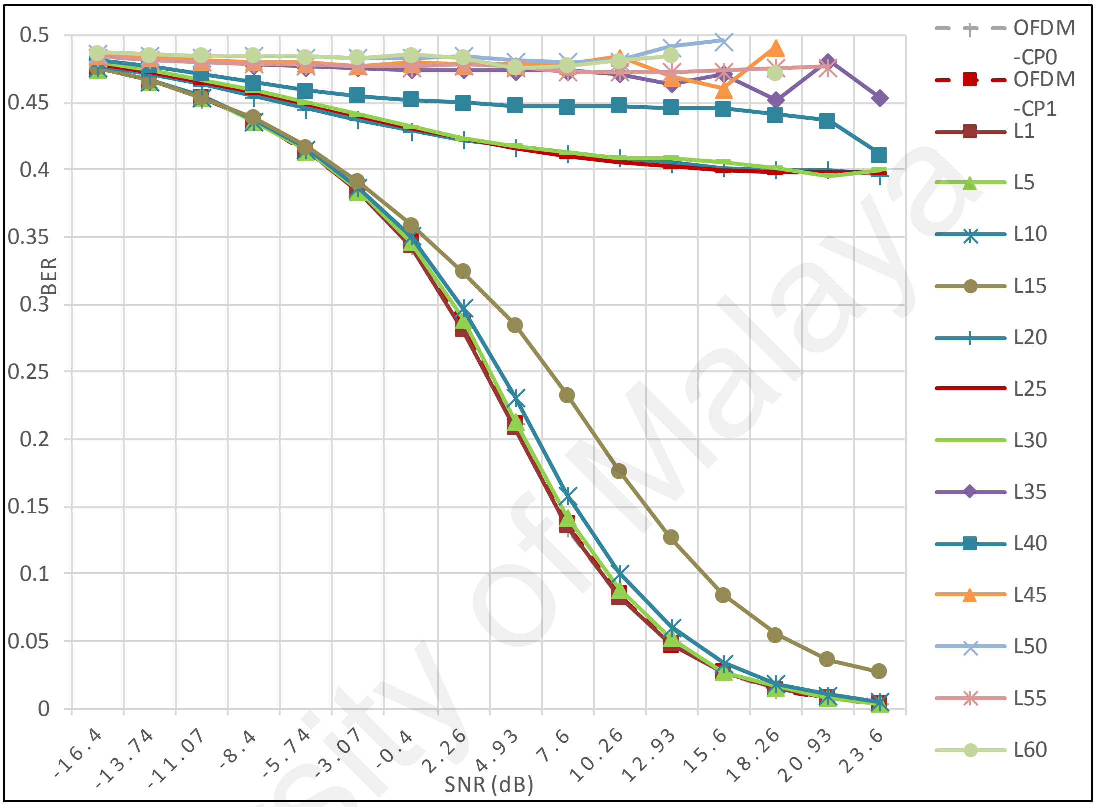

Figure 4.16: BER (coded) versus SNR for UFMC at different filter length with 36 carriers per sub-band.

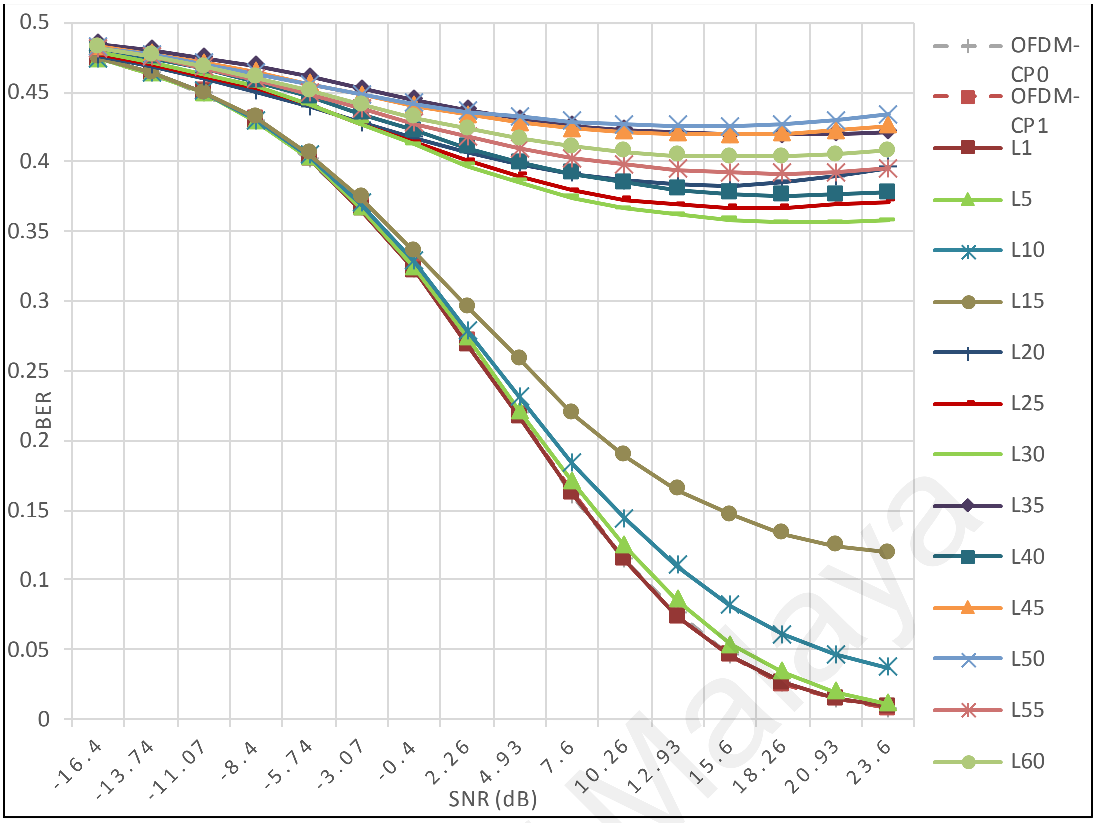

Figure 4.17: BER (uncoded) versus SNR for UFMC at different filter length with 36 carriers per sub-band.

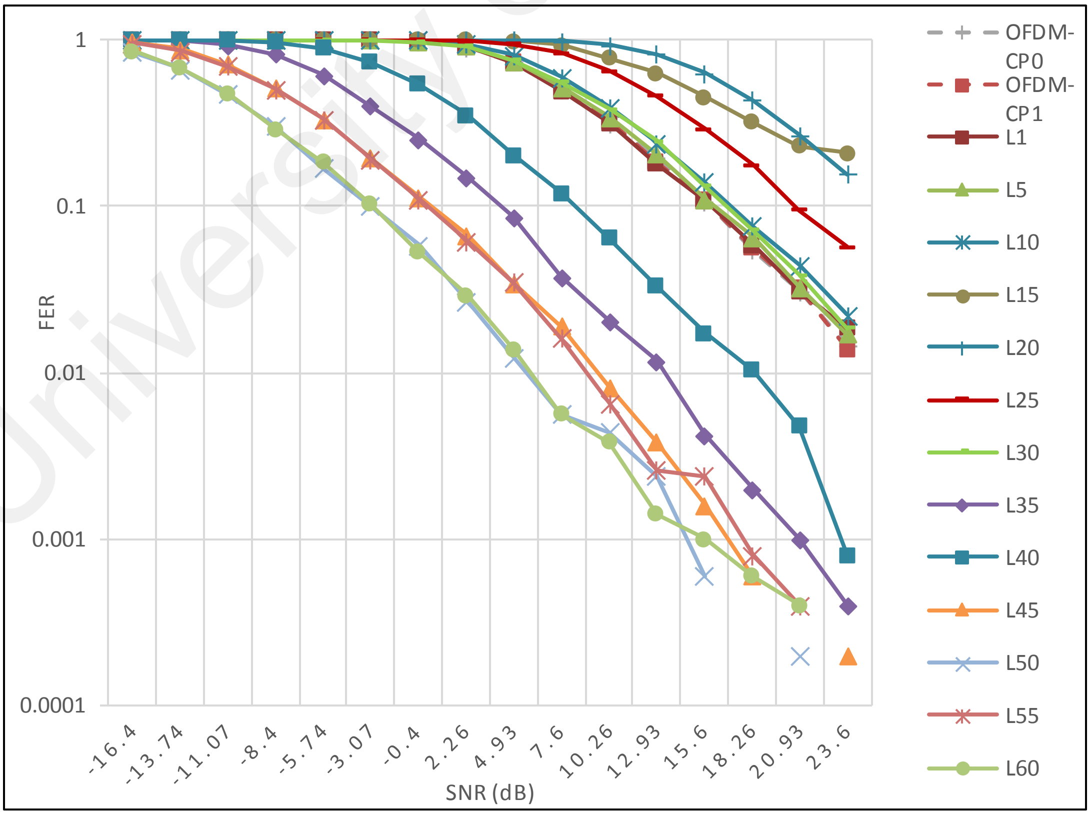

Figure 4.18: FER versus SNR for UFMC at different filter length with 36s carries per sub-band.

For the 18 carriers per sub-band, all UFMC at any filter length is either same or poorer than OFDM for the coded and uncoded BER. For FER, 18 carriers per sub-band has the best profile when L=35 and L=45. This is also the filter length that has the best performance for the throughput. The worst coded and uncoded BER is at L=35 and the worse FER is at L=30.

The simulation result for 9 carriers per sub-band are show in Figure 4.22 to Figure 4.24. Unlike the previous result of different carrier per sub-band, 9 carriers per sub-band of UFMC has the best BER and FER profile when filter length is L=1 and L=15. This is also the best filter lengths for the throughput profile. The worst coded and uncoded BER is at L=25 and the worse FER is at L=55.

For the 1 carrier per sub-band, the result is shown in Figure 4.25 to Figure 4.27, is clear than the best BER and best FER is when L=1. The worst coded and uncoded BER is at L=25 and the worse FER is at L=60.

In this section, based on the observation, we can conclude that BER and FER performance has no direct relationship with the length of the filter. Second observation, different filter length does impact the BER and FER performance.

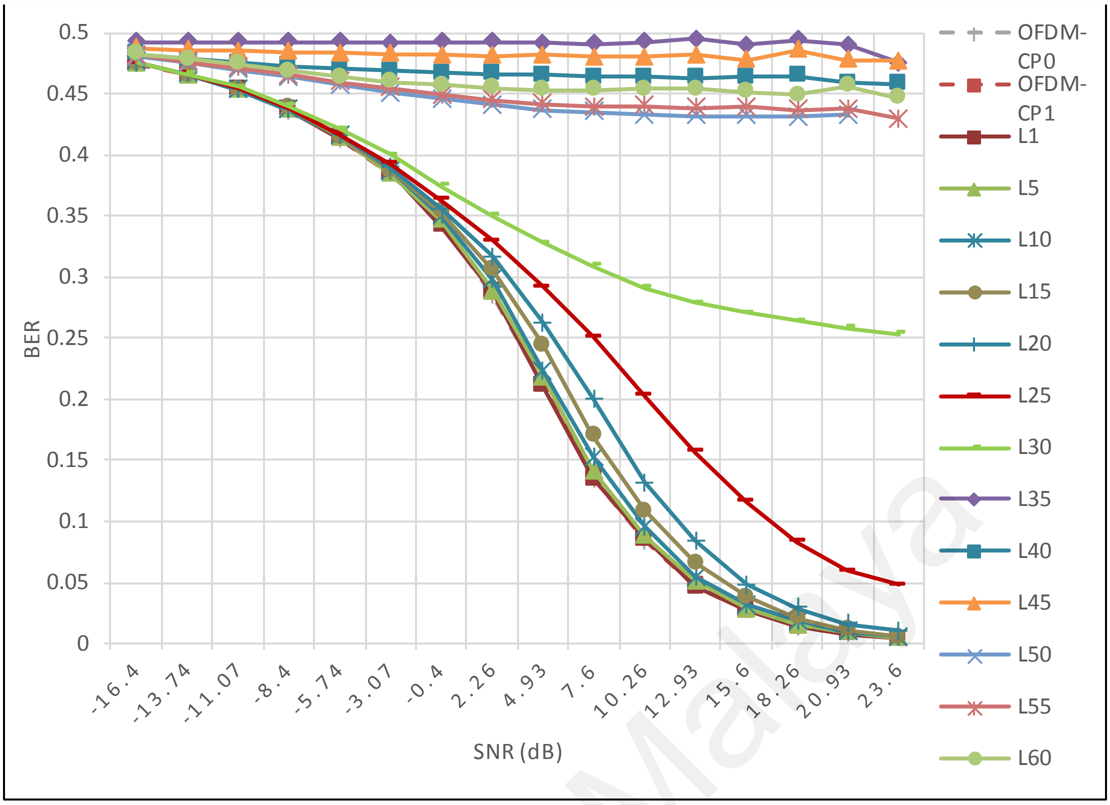

Figure 4.19: BER (coded) versus SNR for UFMC at different filter length with 18 carriers per sub-band.

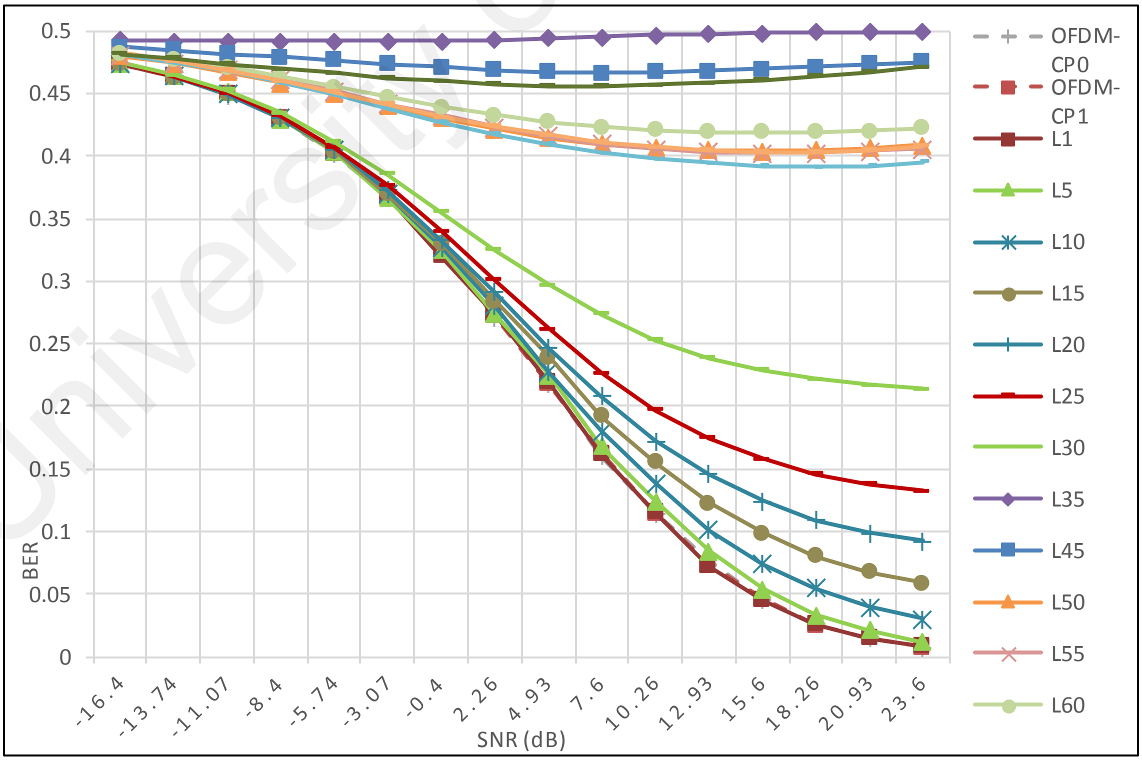

Figure 4.20: BER (uncoded) versus SNR for UFMC at different filter length with 18 carriers per sub-band.

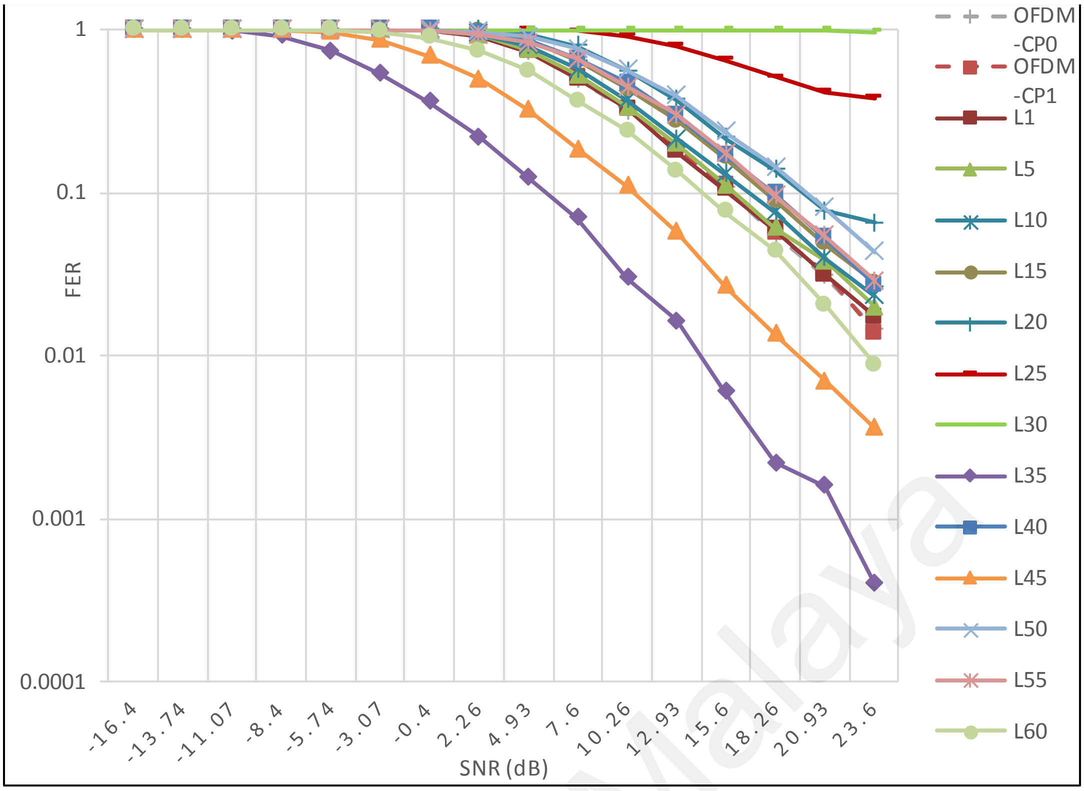

Figure 4.21: FER versus SNR for UFMC at different filter length with 18 carriers per sub-band.

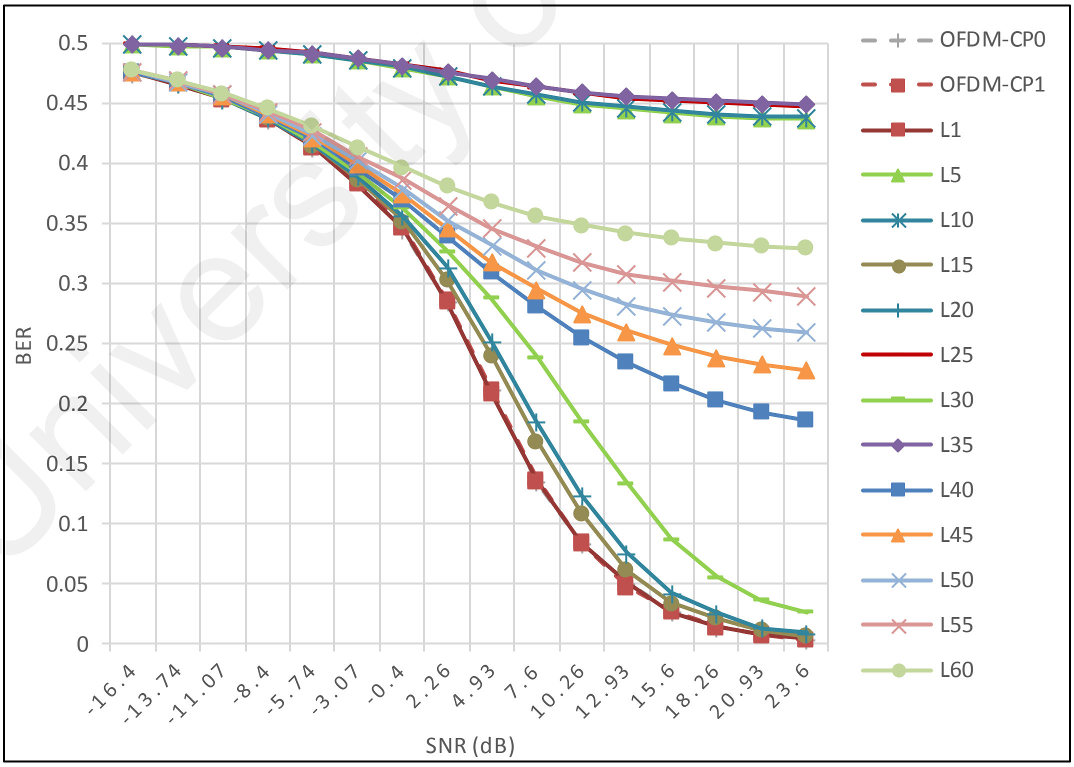

Figure 4.22: BER (coded) versus SNR for UFMC at different filter length with 9 carriers per sub-band.

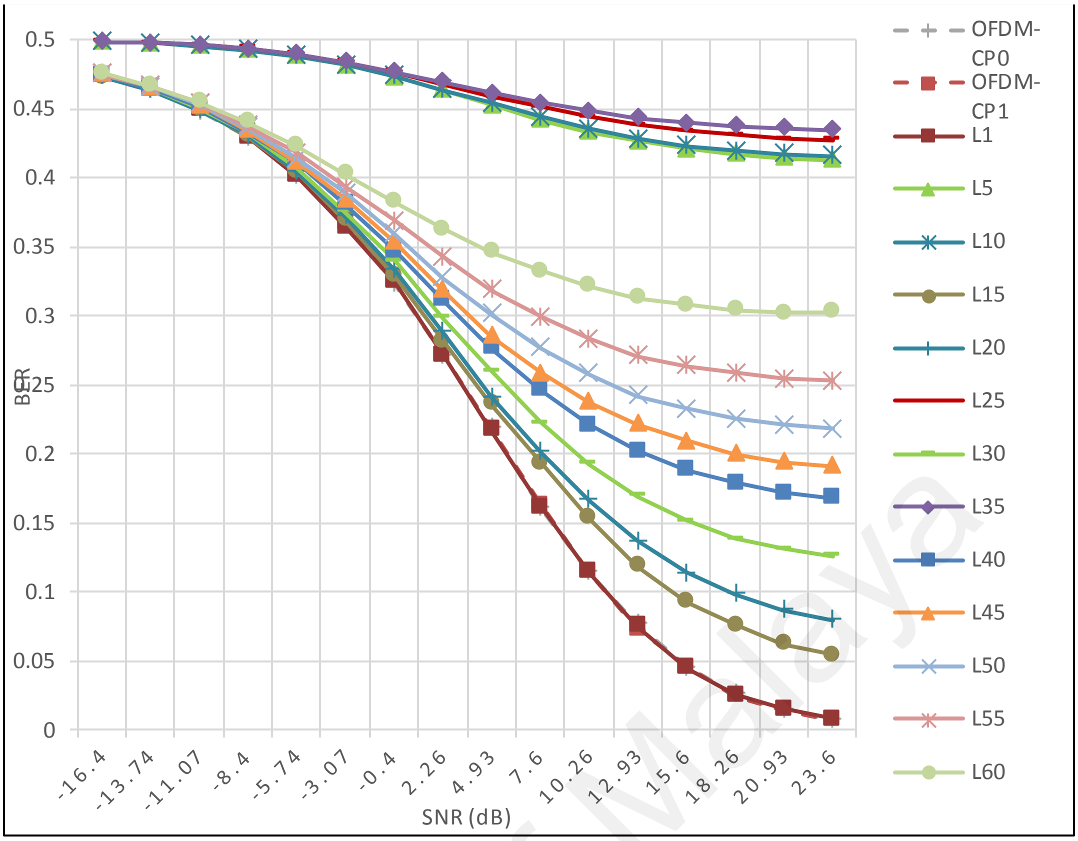

Figure 4.23: BER (uncoded) versus SNR for UFMC at different filter length with 9 carriers per sub-band.

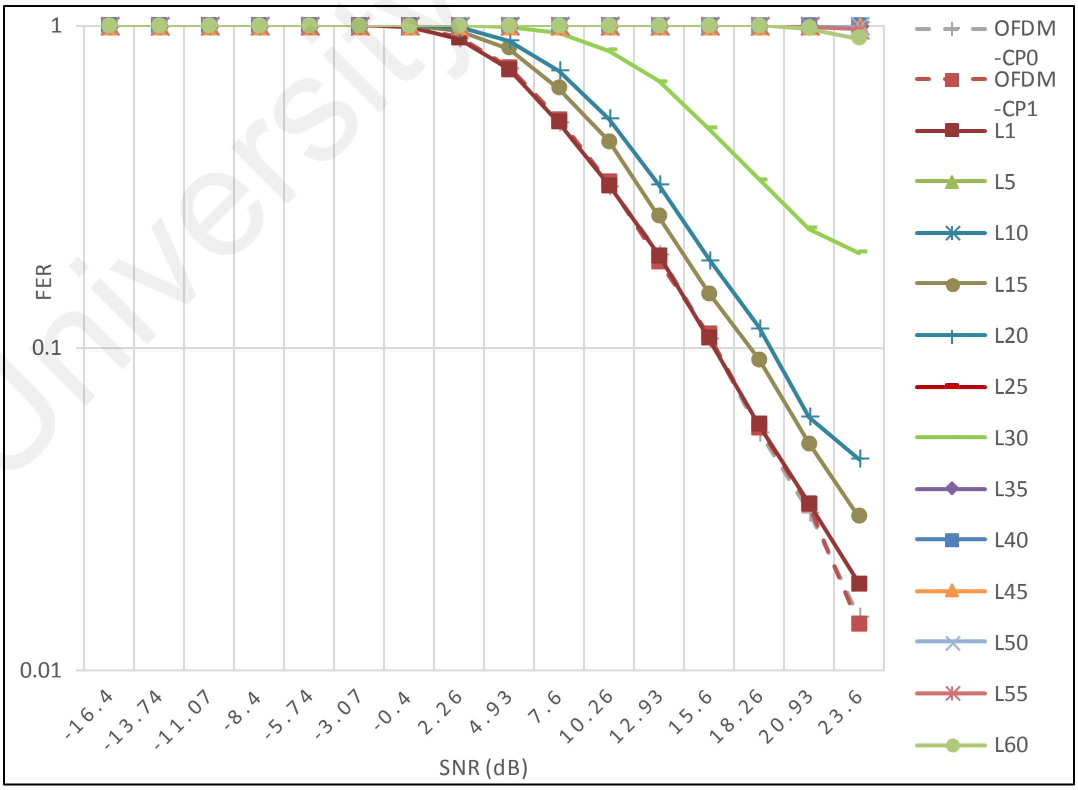

Figure 4.24: FER versus SNR for UFMC at different filter length with 9 carriers per sub-band.

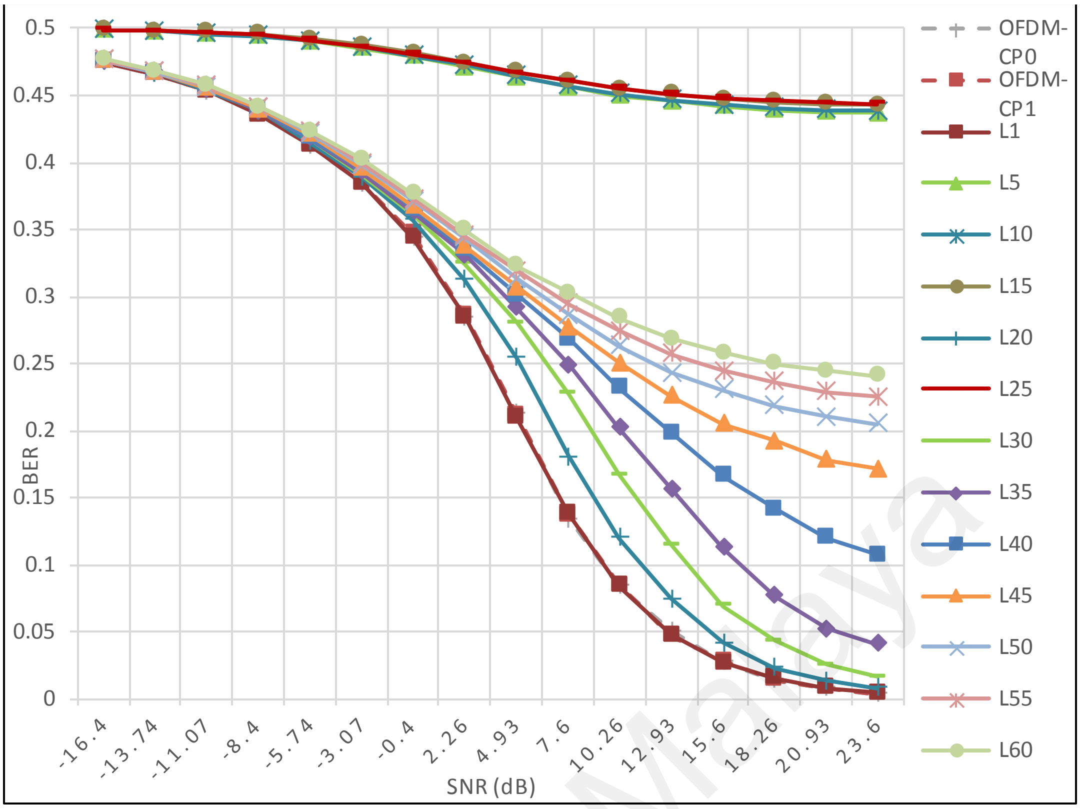

Figure 4.25: BER(coded) versus SNR for UFMC at different filter length with 1 carrier per sub-band.

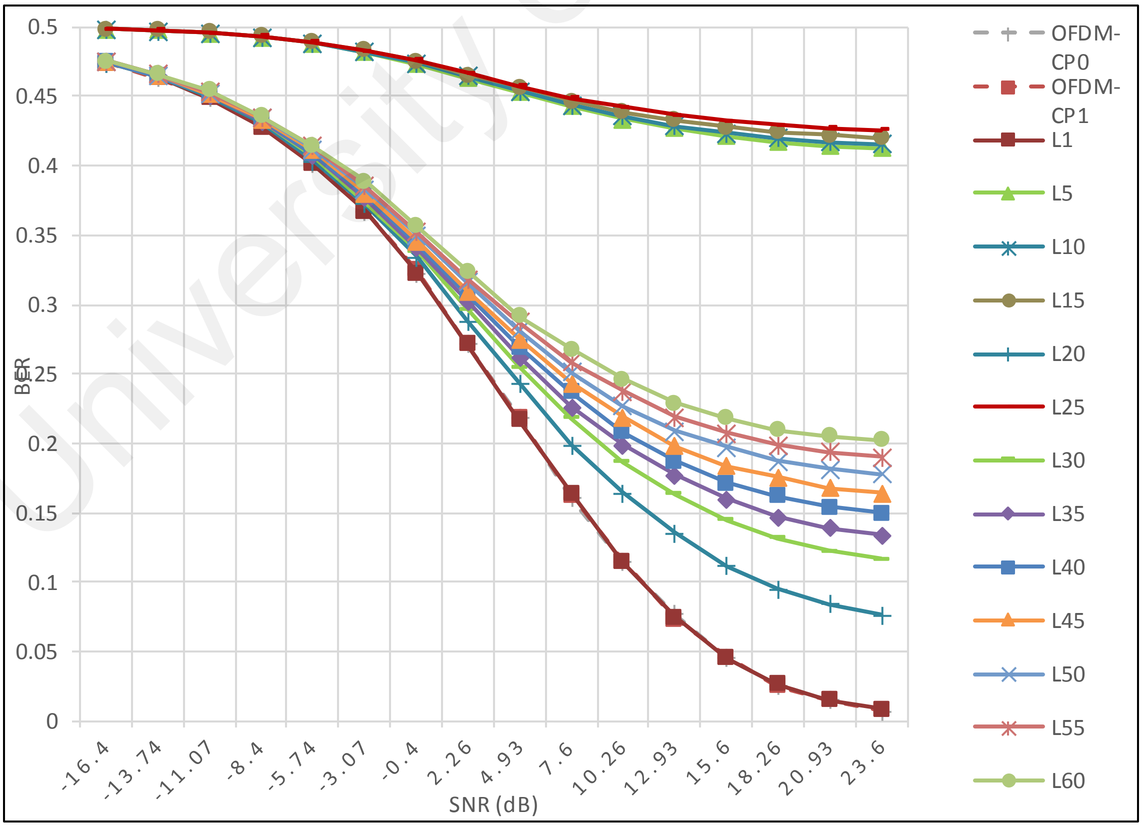

Figure 4.26: BER(uncoded) versus SNR for UFMC at different filter length with 1 carrier per sub-band.

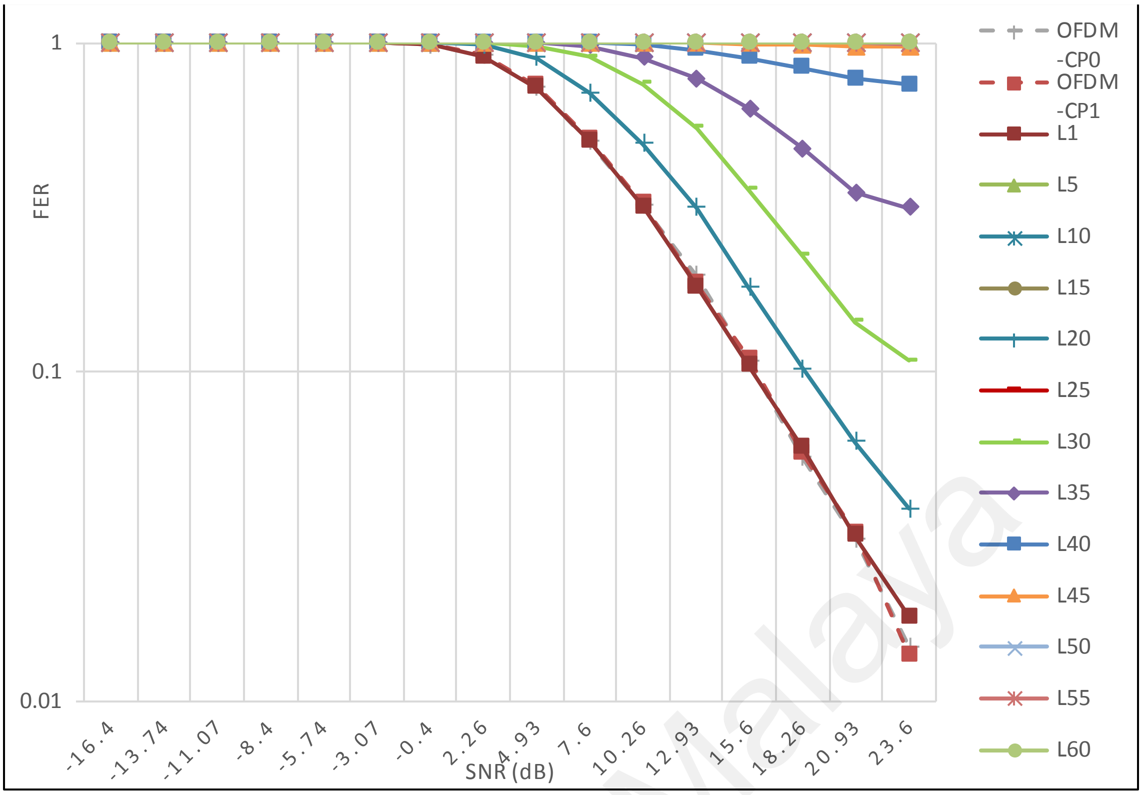

Figure 4.27: FER versus SNR for UFMC at different filter length with 1 carrier per sub-band.

4.3 Summary

From the simulation results, we can conclude that the filter length (L) used in UMFC has no direct relationship to the performance of throughput, BER and FER. However, it can be seen that different filter lengths can impact the performance parameters. UFMC with lower number of carriers per sub-band gives poorer performance than OFDM.

CHAPTER 5: CONCLUSION AND FUTURE WORK

From the simulation results, we can conclude that filter length has no direct relationship to the either throughput, BER or FER. The different filter length however, does impact to the performance of UFMC. The minimum of filter length is 1. Theoretically, the filter length can be infinite. Longer filter length gives lower OOB emission, but will also result in narrower filter bandwidth and increase the complexity of the system. The result suggest filter length selection may based on optimization. This may increase the computation since different carrier per sub-band may require different filter length for optimal performance. In 5G, different services may require different carrier per sub-band.

From the result of simulation in previous section, when filter length equal to 1, it always has the same result when compare to OFDM. This is consistent with equation derivate by Zhang and his team (Zhang et al., 2016).

The future work shall include the modelling and optimization on how to select the proper filter length to achieve best BER, FER, throughput, OOB emission at different number of carrier per sub-band.

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