Université Libre de Bruxelles

ELEC-H422 Wireless communication channels
ELEC-H522 Digital communications

Report: Wireless Communications Project Experimental Simulation of a Multi-User MIMO 5G Small-Cell

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Contents

1 Introduction

This project covers mainly the Channel Characterization, Modelling and the implemention of the OFDM Transceiver which is based on wireless Communication Channels (WCC) and Digital Communications (DC) by bringing them together in a single system to observe the strengths of both fields. The project is driven by a deep understanding of the dualities of Frequency-Delay, Space-Angle, and Time-Doppler that characterize wireless channels and its impact on communication systems. The report then summaries the key results obtained and potential of the components such as cyclic prefix, preamble, Power Delay Profile, RMS delay spread, Coherence Bandwidth among others in the field of wireless and digital communications.This report is limited to channel characterisation in terms of Frequency-Delay Duality for wideband and the implementation the OFDM Transceiver.

2 OFDM-based Communication

The block diagram in 1 represents OFDM-based communication for MIMO systems operating in different scenarios such as wideband and narrowband for Line of Sight(LoS) and Non-Line of Sight(NLOS). In the transmitter block of a MIMO OFDM transciever system, the input data is encoded and mapped to a specific constellation point (QAM) for each symbol transmission. Next, the mapped symbols are fed into a separate IFFT block to convert them into time-domain signals. These signals are then passed through a cyclic prefix block to mitigate the effects of multipath fading in the channel. Finally, the time-domain signals with cyclic prefix are combined and converted into an analog signal for transmission.The noise is modelled as a gaussian distribution with a mean of zero and a variance corresponding to the signal-to-noise ratio (SNR) of the channel. The OFDM signal is then convolved with the channel impulse response in order to simulate the effects of multipath propagation using an equalizer, which is designed to mitigate the effects of the channel on the transmitted signal. In order to ensure a reliable transmission and reception of the OFDM signal, a preamble is added to the transmitted signal to facilitate synchronization and for channel estimation at the receiver. The receiver uses the preamble to estimate the channel response and adjust the receiver parameters accordingly.

The receiver block of a MIMO OFDM transciver system involves several stages. The received signal is first converted to the digital domain and passed through a FFT block to convert it to the frequency domain. The cyclic prefix is then removed from the signal while the demodulated symbols are mapped to their original data. The decoded data is then passed through an error-correction decoder to correct any errors that might have occurred during the transmission. The symbol are combined to form the final decoded symbol. This part is implemented in question 2.

Basically, the parameters given in this project includes the transmit power, ($ch.Ptx$), the top ($ch.wt$) and bottom ($ch.wb$) walls of the channel, the maximum number of reflections, ($ch.rho$), the carrier frequency, ($ch.fc$), the system bandwidth, ($ch.B$), frequency bins, ($ch.Q$), the antenna spacing for MIMO-only, (dr), the carrier wave number, ($ch.\beta$), the path loss constant, ($ch.A$), the number of cluster paths per main path, ($ch.path\_params.Npaths$), and the maximum path delay,

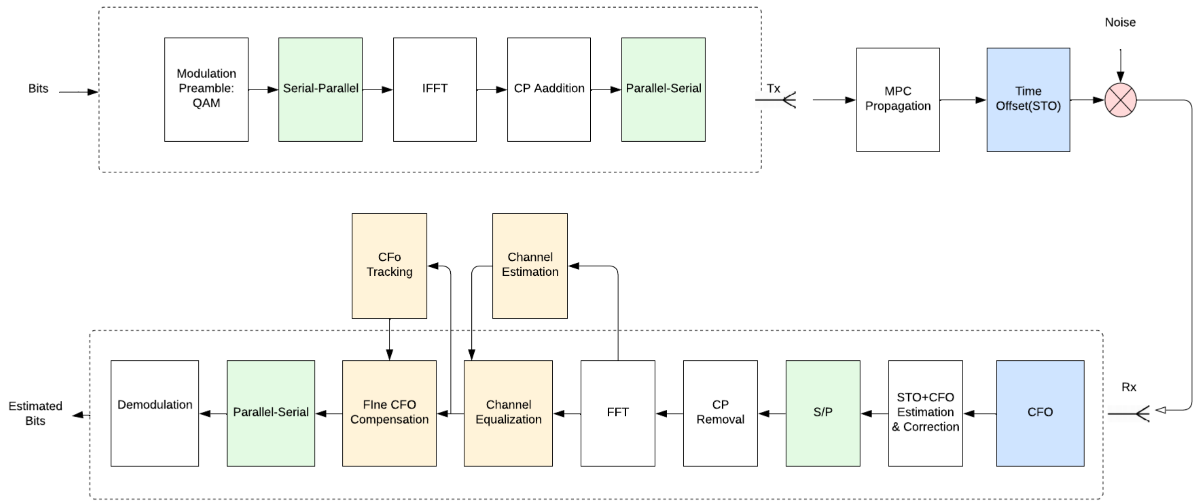

Figure 1: OFDM Chain

Other parameters given in the project are as shown in the table below.

Parameters	**Values**
SNR[dB]	-5:2:40
Bandwidth	100e6
Number of Sub-subcarriers [samples]	1024
Length of cyclic prefix, Q [Samples]	64
Carrier Frequency [GHz]	3.6e9
Data length, Channel Mode [OFDM symbols]	4096

Table 1: OFDM Parameters

3 Channel Characterization and Modelling

During data transmission, the transmitter and the receiver are not at the same location, for example, in an indoor scenarios wireless channel is characterized by a combination of Line-of-Sight (LOS) and Non-Line-of-Sight(NLOS). In the LOS component, there is a direct path between the transmitter and receiver with no obstructions and the signal propagates through the air with minimal attenuation and delay.

In the NLOS component, the signal path is obstructed by walls, furniture and other objects in the environment. The signal is under MPC which results in multiple reflections,delays, diffraction, and scattering before reaching the receiver. By knowing the characteristics of the channel, we can optimize the system parameters such as modulation schemes, coding rates, antenna configurations because we do not know the channel to achieve optimal performance in different communication scenarios.

3.1 Frequency-Delay Duality

Frequency-delay duality occurs when the channel amplitude depends on frequency (i.e., frequency selective fading) due to the spread in delay domain which has effects on the system's performance due to multipath.

LOS (Line-of-sight) propagation condition generally results in lower frequency selectivity and less delay spread,less impact on frequency-delay duality when compared to NLOS (Non-line-of-sight). Moving-LOS propagation condition arises when there is a mobility at both transmitter and/or receiver which causes significant doppler spread and time-varying delay spread depending on the speed of the moving objects.

3.2 Wideband Characterization

The transmission scheme is determined by signal parameters such as signal bandwidth, symbol period, multipath rms delay spread and Doppler spread. The channel transfer function can be characterized based on (1) Coherence Bandwidth, (2) Channel Frequency Correlation.The extent of time or frequency dispersion determines whether the fading is frequency-selective or time-selective. In a wideband channel, the OFDM symbol bandwidth is greater than the coherence bandwidth ($B_c \approx 1/\sigma_\tau$) of the channel i.e B $>> \Delta f_c$ or $\Delta\tau << \sigma_\tau$, frequency-selective fading is induced resulting in inter-symbol interference, the opposite is the case for narrowband model.

3.3 Questions

- **Question: Assuming that the Client is moving, observe the Channel Transfer Function (CTF) for 1, 2, and 10 number of reflections over multiple realizations of the client position. In which cases the CTF is frequency-flat or frequency-selective?**

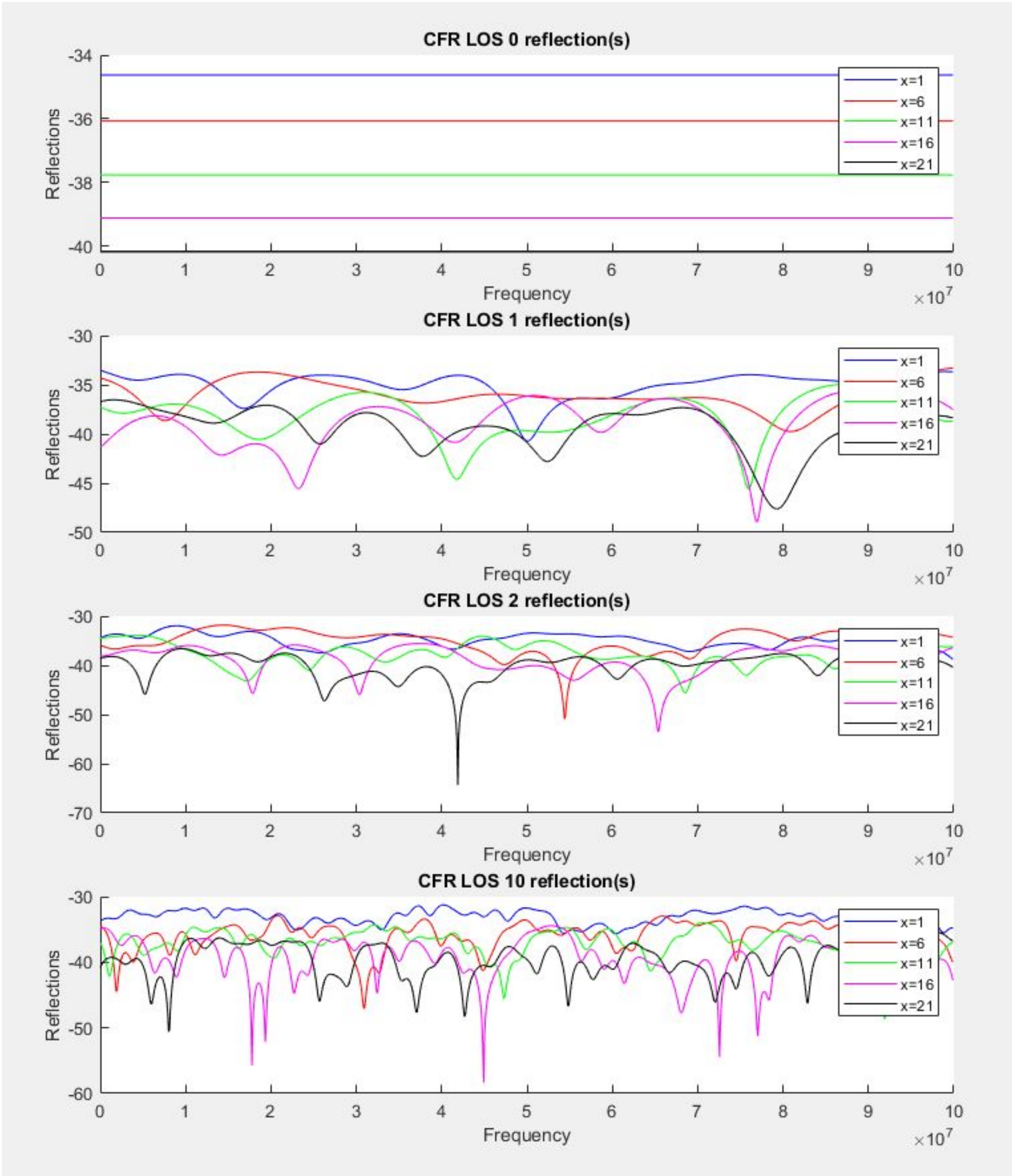

Figure 2: the CTF's for multiple reflections, i.f.o distance, LOS

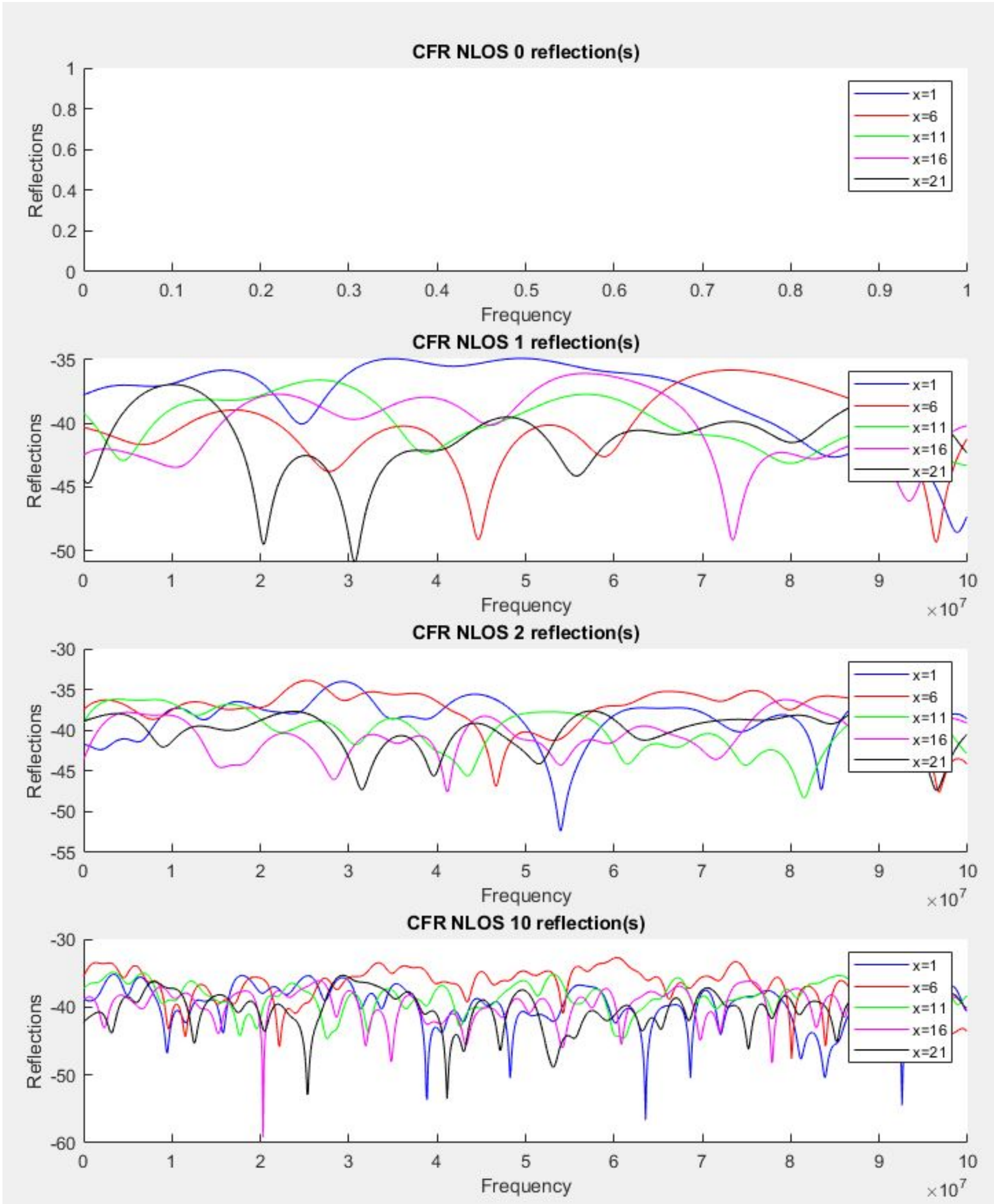

Figure 3: the CTF's for multiple reflections, i.f.o distance, LOS

- **Answer:** As illustrated in figure 3, only in the case of 0 reflection, the CTF is frequency-flat and in the case of no reflections and no LOS-component, the CTF is obviously 0 for all frequencies. In all cases, I noticed an overall decrease in received power, with some exceptions due to interference, the higher the x-coordinate becomes in value, the bigger the path loss i.e the further we have removed the receiver from the sender. In the cases where reflections are taken into consideration, the interference between the multiple paths is totally unpredictable, as seen in 3, by how the frequency-selective CTF seems to vary randomly in function of position, and the amount of reflections allowed in both the LOS and NLOS scenarios.

- **Question: Compute the channel frequency correlation and deduce the channel coherence bandwidth while varying the number of reflections between 0, 5 and 10. Provide reasoning for what you observe as you vary the number of waves.**

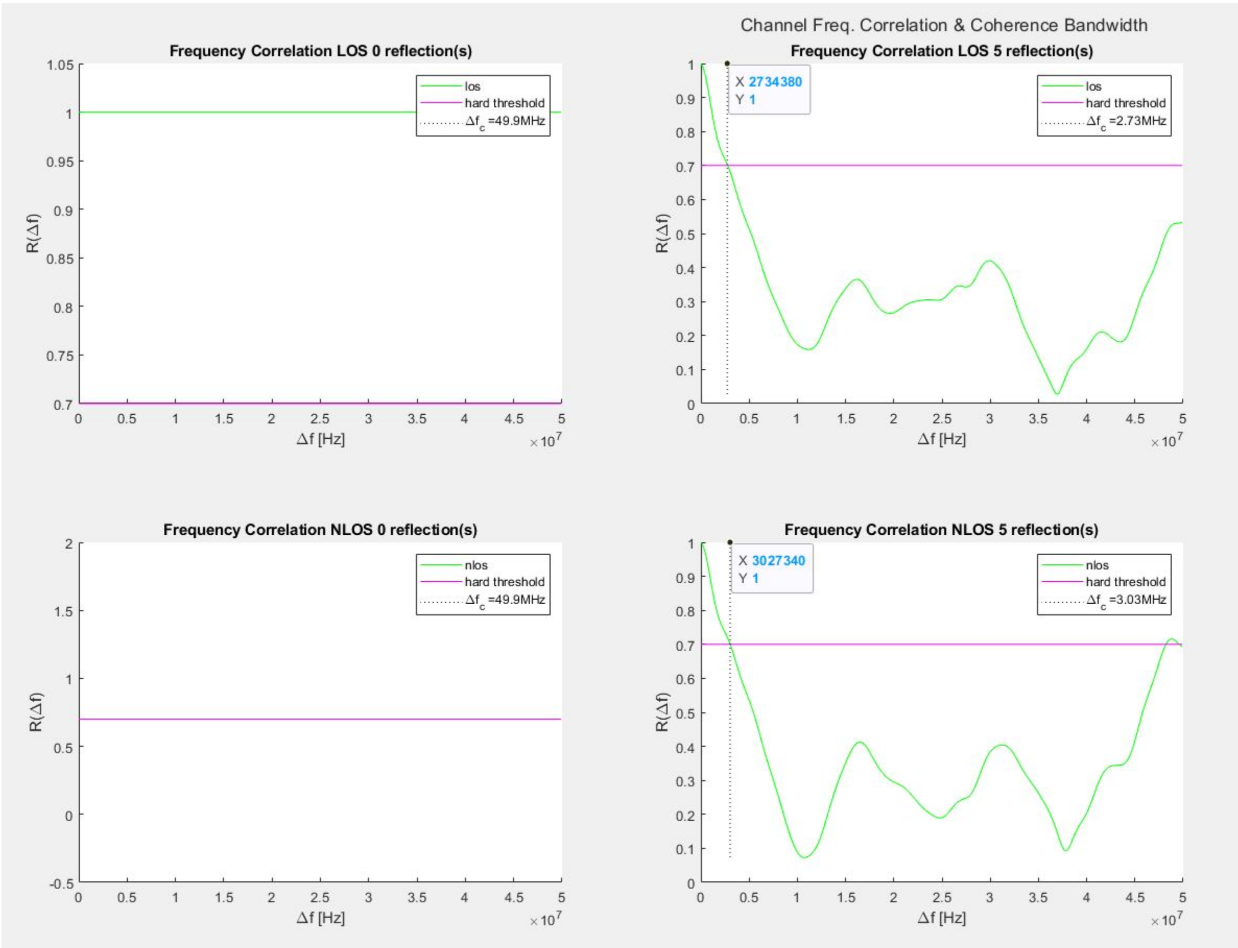

Figure 4: Channel Frequency Correlation i.f.o. n° reflections, LOS and NLOS. Empirical channel coherence bandwidth obtained using a cutoff value

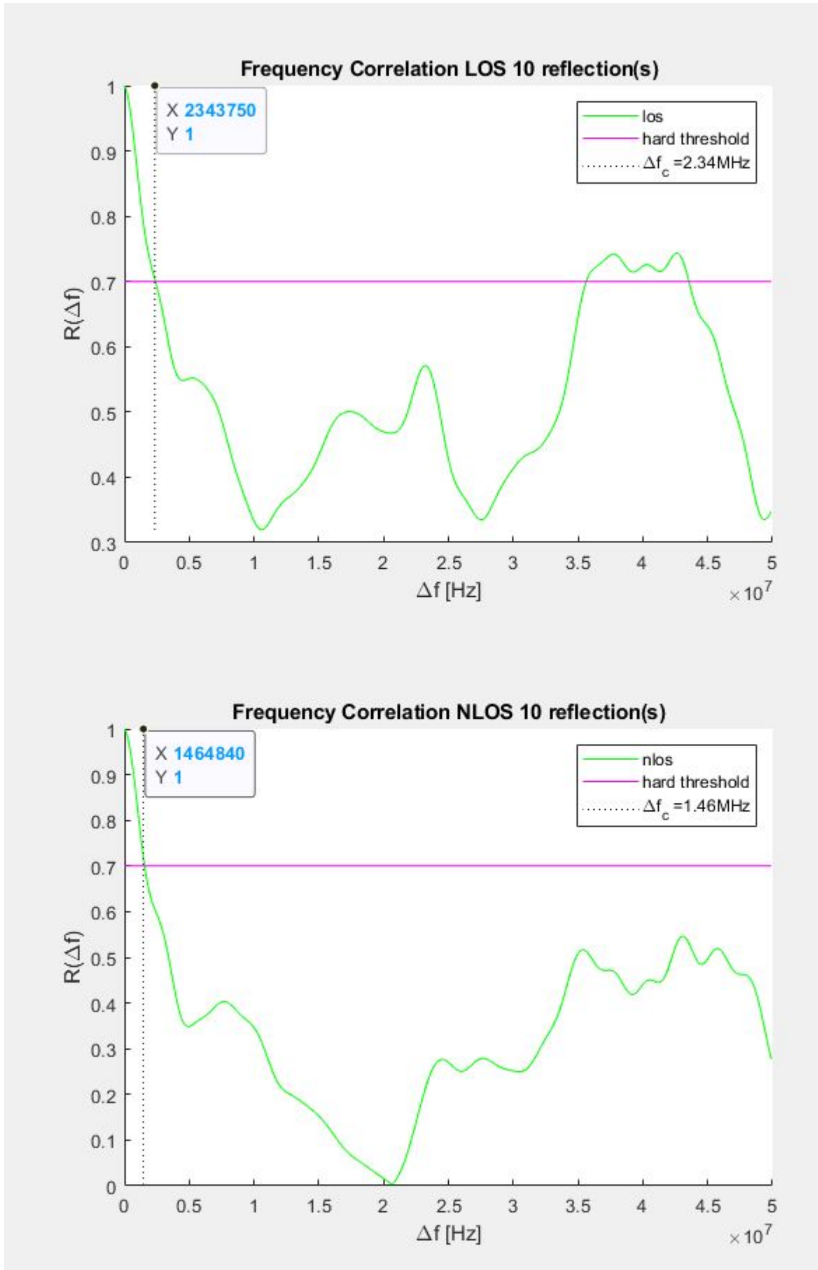

Figure 5: Channel Frequency Correlation i.f.o.number of reflections, LOS and NLOS. Empirical channel coherence bandwidth obtained using a cutoff value

- **Answer:** The frequency range around which the channel frequency response is almost constant is called coherence bandwidth. We selected as a cutoff point for the empirical channel coherence bandwidth, 0.7 times the original value, I normalised the value to 1, so $20log_{10}(0.7)$ on the deciBel scale. Of course, in the case of no reflections (flat fading), the correlation between channel values of different frequencies remains 1, as the correlation between identical values always is 1, except when the values are 0, excluding when looking at NLOS, where no channel correlation is possible, hence the correlation is 0 everywhere. The bigger the amount of reflections allowed, the faster the frequency correlation drops below the hard threshold value (the more frequency-fading the channel behaves), with this dropoff being heavier in the NLOS case, where no sole channel dominates. Note that the results of channel coherence bandwidth are bogus in the case of 0 reflections, since the correlation remains constant as Δf goes to infinity, hence, these fields are left blank in table 3

- **Question: Deduce the Channel Impulse Response (CIR) and compute the corresponding Power Delay Profile (PDP). Provide reasoning on the obtained plot and the simulated multipath channel. Compute the delay spread based on the PDP. Obtain the coherence bandwidth through the delay spread and compare it with the one obtained in the previous step.**

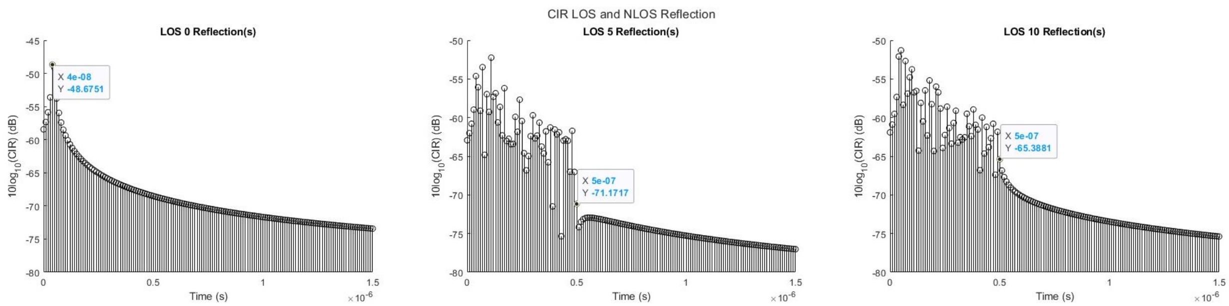

Figure 6: The CIR's for 10 reflections, i.f.o distance, LOS

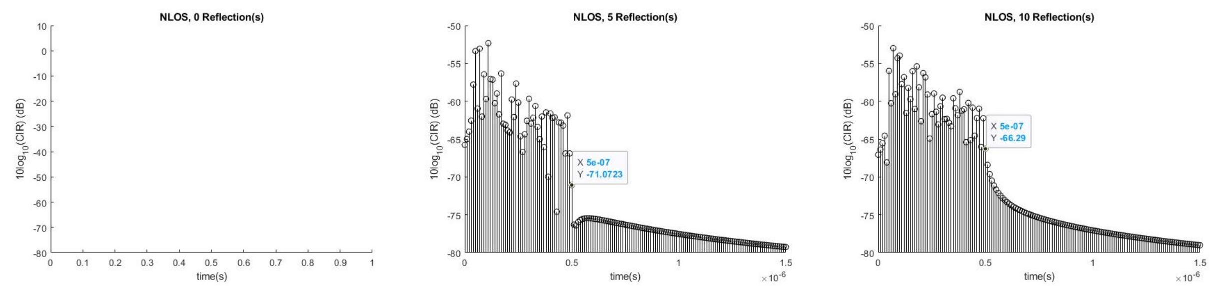

Figure 7: The CIR for multiple reflections, i.f.o distance, LOS and NLOS

- **Answer:** The RMS delay spread involves considering the amplitude of each tap according to its weight at a specific time instant.To illustrate, with a sampling rate of 100MHz, tap separations are 10ns (1/100MHz = 0.01MHz = 10ns). At intervals of 10ns, the delay value is multiplied by the amplitude. This method effectively applies weights to the channel impulse response (CIR) based on the amplitude. In this case the last tap has a small amplitude because it travels a much more longer distance so a high pathloss, in the end the signal that comes from that tap will have a very small contribution on the overall received signal.

  The CIR is complex valued, both amplitude and the phase are present for example phase propagation, attenuation amplitude and then awgn which is complex etc, therefore we use something that will give us the real picture of the delay spread, PDP does this for us.

  Power Delay Profile
  In the PDP we have only the amplitude, no any phase information anymore, the PDP is used to compute the coherence bandwidth (using the delay spread). In PDP complex numbers don't interfere with each other, no constructive or destructive interference with each other in fact every value is real.

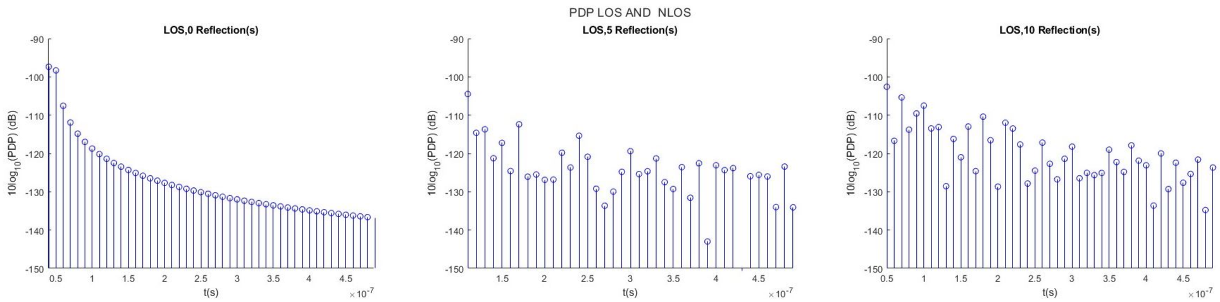

Figure 8: The PDP's for 0,5,10 reflections, i.f.o distance, LOS

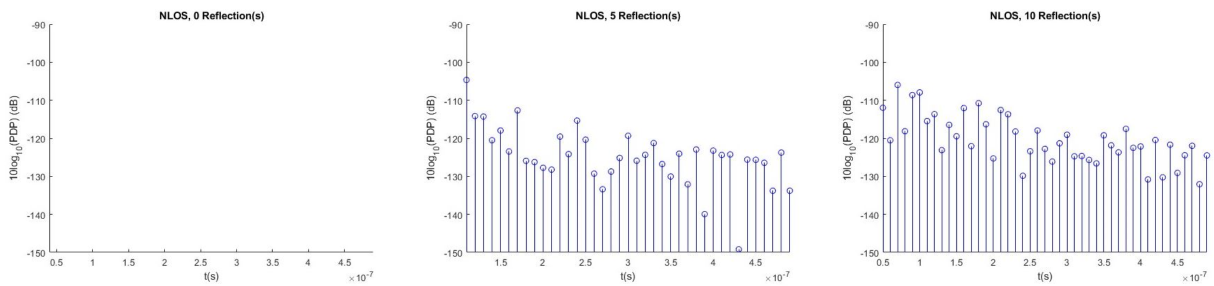

Figure 9: the PDP's for 0,5,10 reflections, i.f.o distance,NLOS

The CIR has been deduced by taking the ifft of the obtained CTFs. The corresponding PDPs, as well as the frequency coherence bandwidth have been written in table 3, the CIR and PDP also have been plotted in figures 7, 8 and 9 respectively.

A few things can be noticed:

- In the case of 0 reflection for no line-of-sight(NLOS), there is no channel, and hence I obtained bogus results for Δf_c and σ_τ, as seen in the table.
- In the case of 0 reflection for line-of-sight channel (LOS), I obtained some delay spread value (I expected hot fading, i.e. $\sigma_\tau = 0$, and hence a frequency correlation smaller than infinity; this can be explained by the leakage between the discrete taps, resulting in the delay having to be spread over more taps than the theoretical tap required.
- in the case of 10 reflections, I received multiple spikes in CIR on few taps (see figure 7), aside from some small tap excited due to leakage: it is clear that the interference between the multiple paths, albeit constructive albeit destructive, results in a non-smooth CIR curve (when compared to the curve of 0 reflection LOS)
- I also noticed that, around 0.5µs, the CIR always seems to die out: this makes the assumption of a hard cutoff I made at 0.5µs for the PDP.
- I observe a substantial increase in total received power (when integrated over the PDP) with reflections permitted. This behavior is expected due to the higher excitation of taps in multipath scenarios, particularly with constructive interference that generates additional strong tap-excitations.

4 Implementing the OFDM Transceiver

It is assumed that the bandwidth of the transmitted signal is smaller than the symbol rate, so that sampling at the symbol rate is sufficient to extract all information from the received signal. It is easier to estimate the channel in narrowband model than in wideband model because wideband suffers more in the presence delay dispersion of the MPC, frequency selectivity, Intersymbol interference (ISI), Intercarrier Interference (ICI),in wideband, each spectral component of the transmitted signal will be affected by different channel gain which is not the case in narrowband. In narrowband model, the $B << \Delta f_{\text{carrier}}$ and $\Delta\tau >> \sigma_\tau$, as discussed already in question 1 above, these phenomena are observed in OFDM transciever in terms of the narrowband and wideband models, then how can we improve on the wideband model in multipath channel?. When we transmit a sequence of blocks of symbol, the blocks will interfere with the few samples onto the next block. Interestingly, when cyclic prefix is used, those extra samples fall under cyclic prefix on the previous block, since we discard the cyclic prefix and we do the same for the next block, then we discard the interference between the different blocks.

The parameters to pay attention to in designing an OFDM waveform to make sure that the overall coherence bandwidth is sufficiently large includes symbol duration, cyclic prefix length and sub-carrier spacing. To compute subcarrier spacing, for example, the formula to compute the sub-carrier spacing is

$$\frac{Bandwidth}{\text{Number of subcarriers}}$$

Let symbol duration be T, 1/T= Subcarrier Spacing. In narrowband with flat fading, coherence bandwidth should be smaller than subcarrier spacing while in wideband with non-flat fading, coherence Bandwidth should be larger than subcarrier spacing.OFDM waveform is parameterized based on the coherence bandwidth, coherence bandwidth is given by the formula

$$df > \frac{B}{Q}$$

i.e

$$CoherenceBandwidth = \frac{\text{Channel Bandwidth or the signal Bandwith}}{\text{Number of Subcarrier}}$$

.

Generally, from figures 10 to 12, we can see that as the SNR increases the BER decreases for all curves. However, more bits per symbol results in higher BER values at the same SNR. Therefore, a fewer bits per symbol is preferable for achieving better SNR-BER performance, but then of course I need to send more symbols for the same amount of data, without neglecting the importance of extra overhead and efficient use of data resources features.

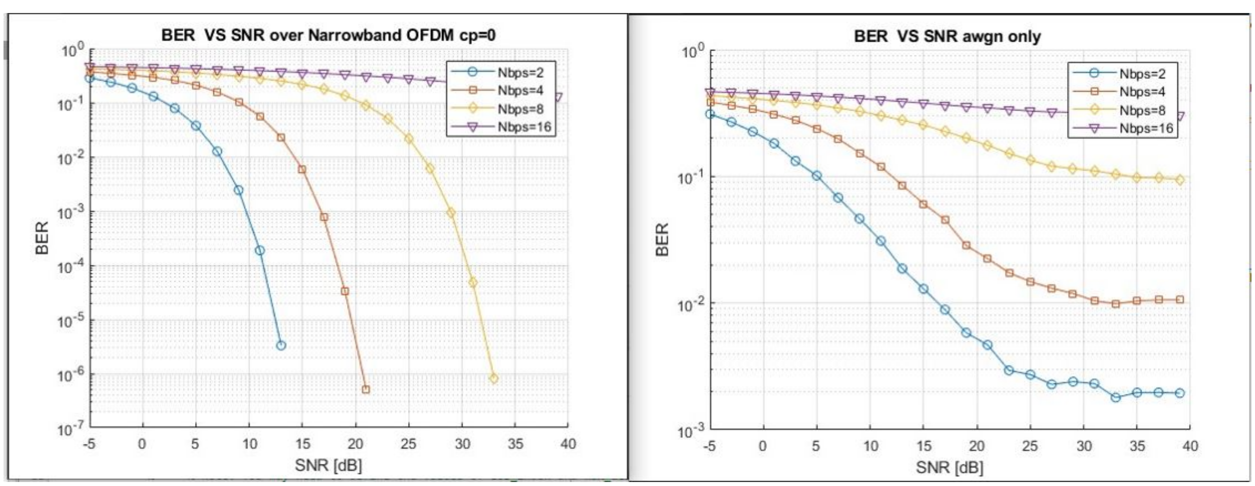

Figure 10: The BER curve in the narrowband model and wideband model with no cyclic prefix: a normal curve only for narrowband but wideband curve is not normal for an effective data transmission

The BER curve in the wideband model
With no cyclic prefix, the error resilience is poor and increasing the SNR only increases it up to a certain point; with fewer bits per symbol during QAM modulation, the BER is less improved than in narrowband in figures 10

4.1 Question

- **Question: Based on the analyses in 1.1, determine what should be the cyclic prefix (CP) length for the given scenario, and implement it in your transceiver. Then, simulate the OFDM system for randomly generated multipath channels. Assess the performance degradation**

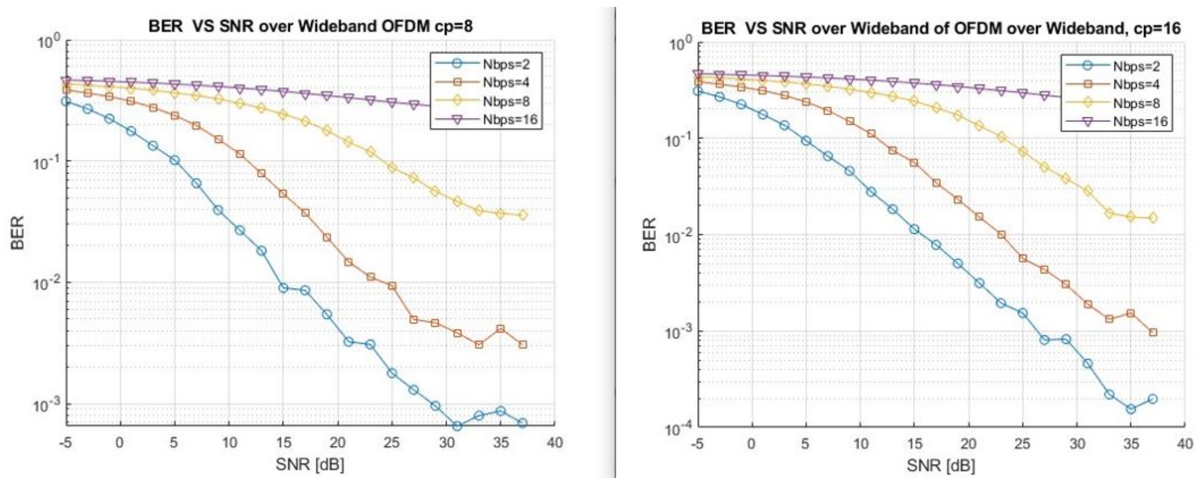

Figure 11: The BER curve in the wideband model with theoretical cyclic prefix of 8 and 16 symbols: the BER improves but then the forming of a BER floors after a certain SNR level remains and then this is still in degraded form.

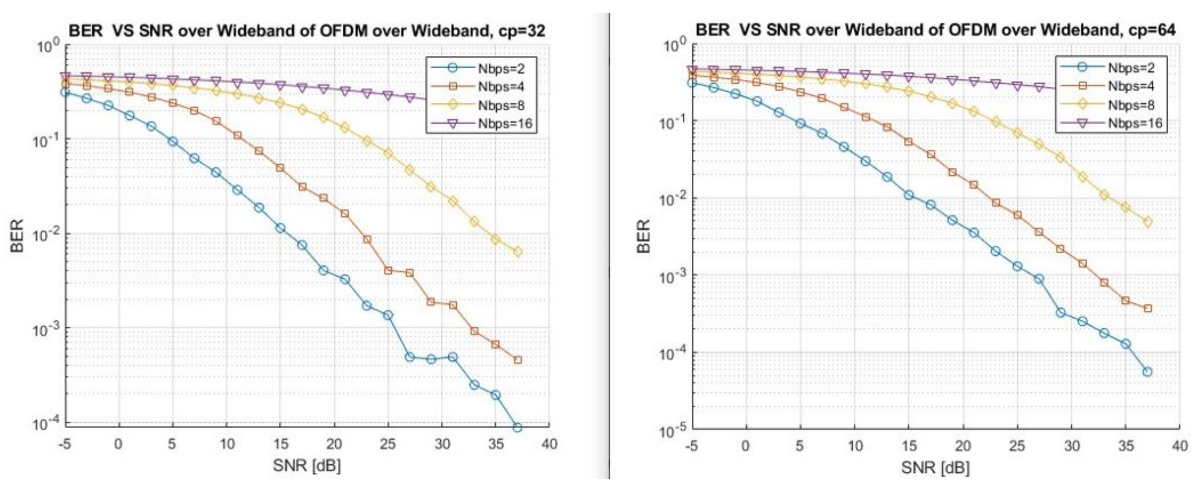

Figure 12: The BER curve in the wideband model with a higher cyclic prefix: now, the BER curves start to improve and increasing the SNR keeps decreasing the BER

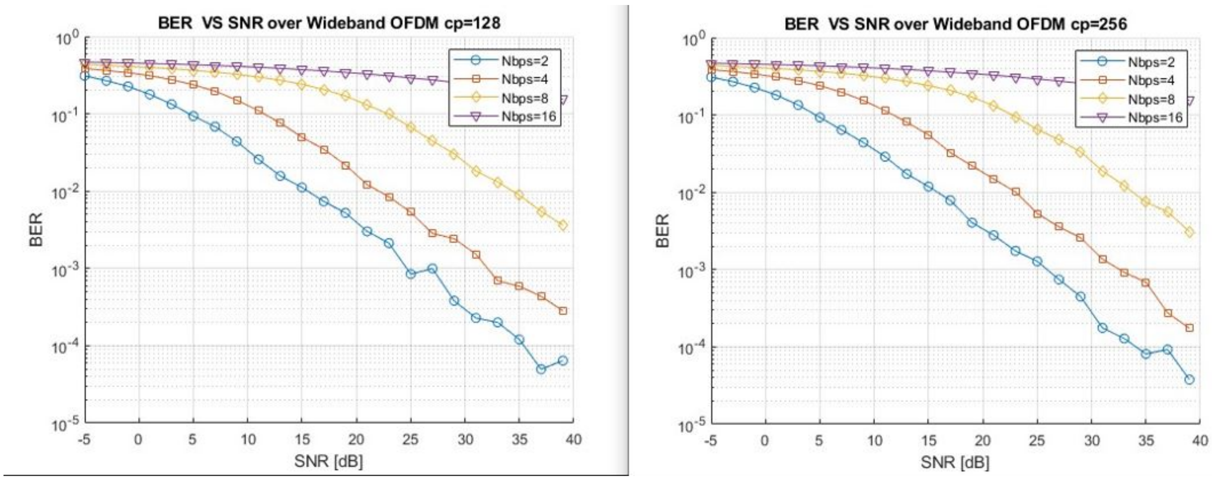

Figure 13: BER performance of the OFDM transceiver is much more better, however overhead computation and efficient use of resource has to be maintained

As can be seen in figures 11 and 12, the asymptotic curve of the BER starts getting improved and the BER-SNR curve changed rapidly starting fom when Cp length exceeds 0.5μs delay spread, until the normal curve is obtained similar to OFDM narrowband model BER- SNR.

- **Answer:**The delay spread is the delay experienced over the whole channel response. The cyclic prefix length should be larger than the delay spread over all the channels, however the cylco prefix length should not be too large than the delay spread over all the channels. Theoretically, as the CIR dies out after 500 bins (corresponding to 0.5µs), we would need a CP of at least length 500 as well. However, figure 11 illustrates an improvement in BER still not the ideal BER-curve as shown in figure 12.
- **Question: Why don't we just make the CP length equal to the OFDM symbol length, or half of it?**
- **Answer:** The CP length should not be equal to the OFDM symbol length or half of it to avoid inefficient use of available bandwidth.The CP length is chosen to balance the trade-off between decreasing the effect of the ISI and wasting the available channel capacity on CP-symbols.
- **Question: What is the impact of subcarrier spacing on the OFDM symbols? Why don't we pick a very small subcarrier spacing, e.g., 100 Hz?**
- **Answer:** The subcarrier spacing affects the duration of the OFDM symbols and the spectral efficiency of the system. Duration, T of an OFDM= $\frac{1}{subcarrierSpacing}$, for example, $\frac{1}{ds}$ where ds is the subcarrier spacing, T= $\frac{Q}{B}$ which implies Q=Duration of OFDM symbol $\times$ $Bandwidth$ since subcarrier Spacing is ds=$\frac{B}{Q}$.

  For example, if the cyclic prefix is 1.125 i.e 12.5% of the original OFDM waveform, in that case the total duration = T $\times$12.5% . Therefore the duration of an OFDM symbol without a cyclic prefix just OFDM is $\frac{1}{\text{Subcarrier spacing}}$ and you can multiply this value with the ratio of cyclic prefix length and the length of OFDM symbol. Smaller subcarrier spacing leads to longer OFDM symbols and narrower subcarrier bandwidth, which can increase the sensitivity to frequency offsets and reduces the ability to combat inter-symbol interference (ISI), larger number of subcarriers and higher processing complexity, which can increase the hardware and computational requirements of the system.
- **Question: With OFDM, can we make a narrowband assumption per subcarrier? If yes, when? If not, why?**

- **Answer:** Yes, with OFDM, we can make a narrowband assumption per subcarrier, as a small bandwidth makes frequency-selective fading resembles flat fading. This assumption of course only makes sense when the subcarrier bandwidth is much smaller than the coherence bandwidth of the channel.
- **Question: Add the preamble in front of the data symbols, i.e., compose the OFDM frame structure. Integrate the low-complexity channel estimation and equalization into your OFDM transceiver. Assess the channel estimation accuracy with Mean Square Error. Assess BER performance.**
- **Answer:**

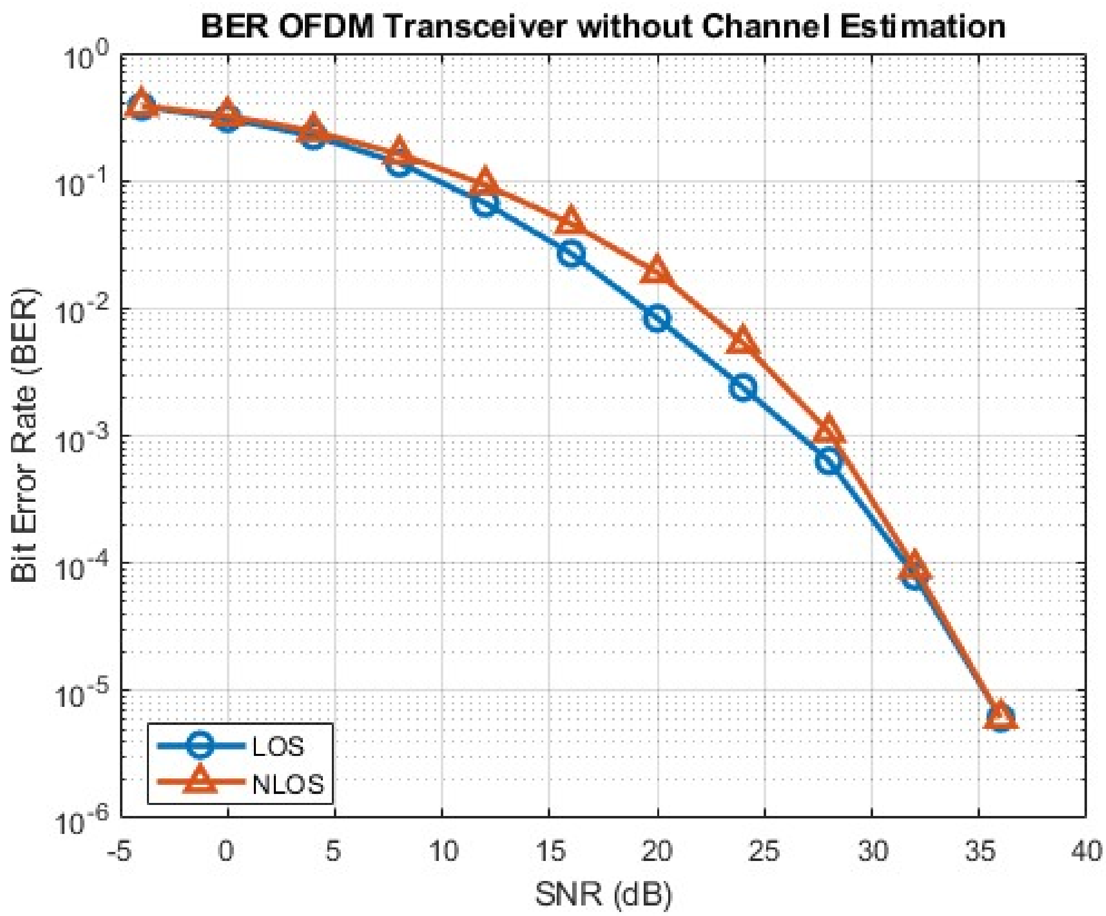

Figure 14: BER for OFDM Transceiver without Channel Estimation

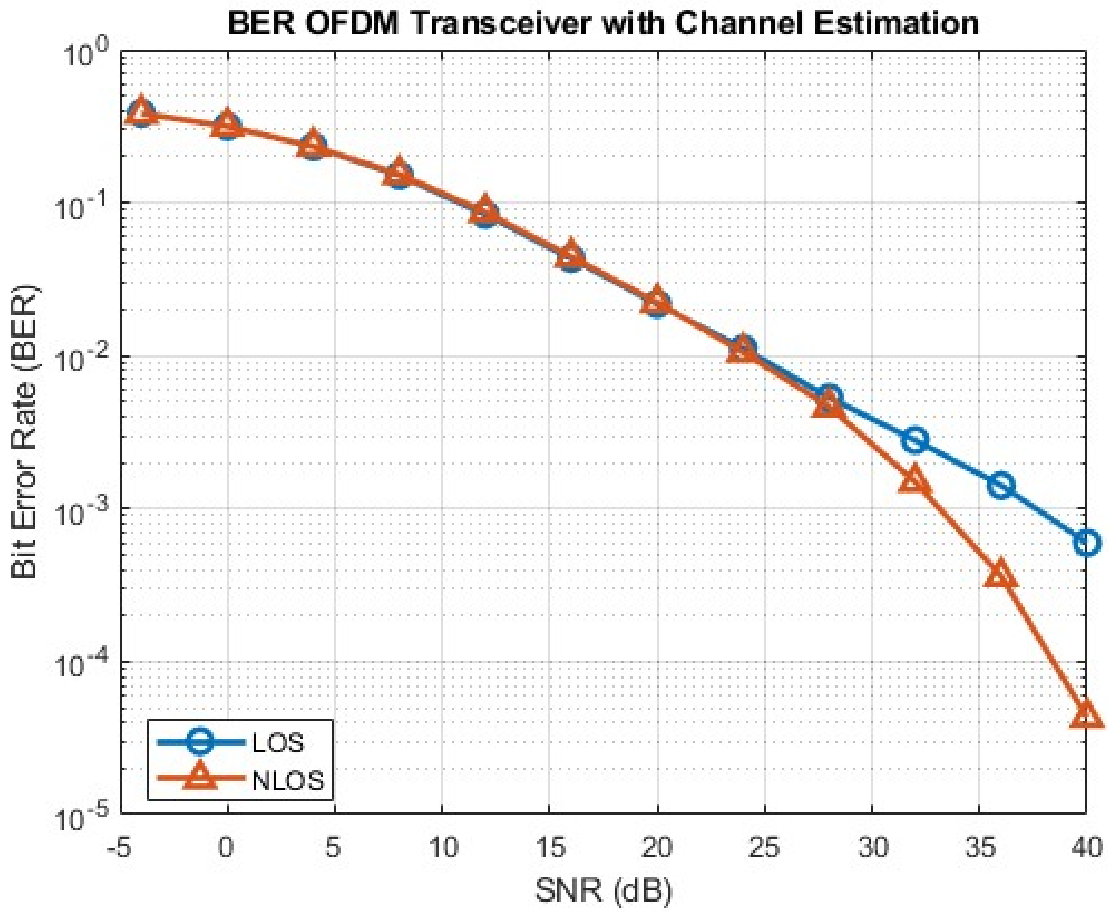

Figure 15: BER for OFDM Transceiver Channel Estimation

By comparing the BER values and the curve 15 obtained for BER vs SNR with (LOS: 2.5472e-14; NLOS: 3.2034e-14) and without channel estimation (addition of preamble) for both LOS and NLOS scenarios, we can see the effectiveness of channel estimation in improving BER performance which leads to a better equalization, resulting in lower BER values compared to using the original channel response directly 15 in the presence of multipath.

4.2 Result summary

		0 reflection	**5 reflections**	**10 reflections**
LOS	rms delay Spread [μs]	1.848	2.209	6.367
	Coherence Bandwidth [MHz]	0.541	0.453	0.157
NLOS	rms delay Spread [μs]	/	7.33	8.579
	Coherence Bandwidth [MHz]	/	0.136	0.117

Table 2: Delay Spread value obtained on Power Delay Profile with respect to the number of reflection

Coherence Bandwidth $)\Delta f[MHz]USingThreshold$	**0 reflection**	**5 reflections**	**10 reflections**
LOS	/	3.03	1.76
NLOS	/	2.83	1.67

Table 3: Coherence bandwidth Numerical values with respect to the Number of Reflections

With reference to the table and figures shown above, CIR died out after 0.5μs, B = 100Mhz, I choose cyclic prefix length at least 50 ($\approx$ 64) to avoid interference between OFDM symbols, cutoff at this value is chosen as maximum delay spread as can be seen in figure 8 and 9 In CIR, there is a spread over multiple taps which implies leakage and Frequency-selective with interference between multiple paths (constructive + destructive), as shown in figure 7. I obtained the same logical conclusion just as it is in figure 3 for the coherence bandwidth, but the numerical values differ (more in LOS-case)

5 Conclusion

Indeed OFDM transforms the convolutive channel in multiplicative channel by applying an inverse Fourier transform at the transmitter and FT at the receiver, since it is not efficient to generate an infinitely periodic signal, an identical received block can however be generated by transmitting a finite sequence when the channel is of finite length L, cyclic prefix of length Ł$_{cp} \geq L$ is effective in preventing interference between OFDM symbols being the repetition of block last samples to make the received block cyclic. More so,PDP is more suitable than CIR for estimating the rms delay spread because in PDP complex numbers don't interfere with each other, no constructive or destructive interference with each other, every value is real (no complex value and phase) also using rms delay spread gives a more realistic characteristic of a wireless channel than using hard-threshold in the presence of multipath wireless channel.