Analysis of cyclic prefix length effect on ISI limitation in OFDM system over a Rayleigh-fading multipath

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ABSTRACT
In this work, the influence of the cyclic prefix on the performance of the OFDM system is studied. We worked out an OFDM transceiver using a 16 QAM modulation scheme, a comparison of the BER for various lengths of the cyclic prefix has been achieved, and the influence of the noise introduced in the channel has been highlighted, for both a Gaussian and Rayleigh noise. The simulation was carried out on MATLAB where the curves of the BER for various lengths of the cyclic prefix are given and compared. We also adopted as a metric the QAM constellation to show the dispersion of the carriers as a consequence of the transmission channel, the mitigation of this effect by the CP is noticeable.

Keywords: AWGN, CP, ICI, ISI, OFDM, Rayleigh

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1. INTRODUCTION
One of the major issues in telecommunication is to adapt the information to be passed over a channel to the channel characteristics [1]. For frequency selective channels, an efficient technique is to use a multi-carrier modulation in which the blocks of information are modulated by the Fourier transform [2]. This technique known as orthogonal frequency division multiplexing (OFDM), showed to be very efficient [3]. The information is transmitted on N different sub-carriers [4], every sub-carrier having an interval of time multiplied by N [5]. By assigning various sets of sub-carriers to various users, the transmitted carriers are orthogonal between them, Therefore allowing every user to make correspond his symbols of data to the corresponding sub-carriers. The system is N times more robust against the inter-symbol interference (ISI) whereas the global rate of transmission remains identical. The spectral efficiency of the OFDM modulation is thus excellent because sub-carriers can overlap. Nevertheless, the most difficult issue to deal with is the inter symbol interference (ISI), resulting from the multipath distribution of the signal on the transmission channel [6], the use of cyclic prefix in the emission allows to reduce the complexity of terminals through the use of FFT algorithm [7].

The mathematical model of the ISI can be obtained by performing a linear convolution of the impulse channel response with the bit stream in time domain [8]. The Inter carrier interference (ICI) reflects the loss of orthogonality between the carrier frequencies as a result of the channel frequency response [9]. The cyclic prefix reduces at the same time ISI and ICI by transforming the linear convolution into a discrete one by inserting the CP at the beginning of each block [10]. To this end, different ICI cancellation methods have been proposed in the literature, In [11] authors presented the multilevel soft frequency reuse (SFR) which aims to limit and manage the inter-cell interference, this method uses cell sectorization, in which each
sector antenna covers a particular region of the cell, despite its efficiency in reduction ICI, this method decreases the capacity in the cell. Reducing each customer throughput implies a reduction in spectral efficiency. Some other studies and techniques like MMSE [12] have been introduced [13] to limit the effects of ICI and ISI, these approaches require a high complexity in their implementation, whether on transmitter or receiver side. In [14] a residues coding scheme is designed in order to measure the ICI levels, optimizing conventional ICI mitigation techniques implemented in MIMO-OFDM. Despite the fact that all the previous techniques can lead to a significant reduction of the noise ratio, but none of them fully satisfies the criteria of balancing complexity and efficiency.

In this research we aim to mathematically analyse the effect of CP, and demonstrate its ability to mitigate the ICI and ISI effects in realistic wideband communication scenarios, the proposed scheme can be easily implemented because of its low complexity, simplifying the equalization at reception, while increasing significantly the signal to interference ratio. The rest of the paper is organised as follow: section 2, the paper provides some basic channel models. Section 3 and 4 provide an analysis of the OFDM system. Section 5 describes the multipath effect. Section 6, presents an overview of th cyclic prefix. In section 7, we provide the simulation results in order to demonstrate the system efficiency and finally the conclusion is provided in section 8.

2. OFDM CHANNEL MODEL

2.1. AWGN channel

AWGN Channel is the simplest channel [6] and the only parameter is the SNR [7] as shown in Figure 1.

2.2. Rayleigh channel

The channel impulse response of Rayleigh multipath channel could be expressed as [4], and modelled as illustrated in Figure 2 [6].

\[ h(t, \tau) = \sum_{k=1}^{L-1} U_k e^{j\phi_k} \delta(t - \tau_k) \]

where L is the number of paths, \( \tau_k \) is the delay of the \( k^{th} \) path, \( U_k e^{j\phi_k} \) is the gain coefficient.

![Figure 1. AWGN channel model](image1)

![Figure 2. Rayleigh channel model](image2)

3. OFDM TRANSMISSION SCHEME

Figure 3 depicts a classical OFDM transmission scheme. The input data sequence is baseband modulated, using modulation schemes such as (BPSK, QPSK, QAM) in our system, 16 QAM method has been used in order to encode the binary information. The data symbols are converted from serial to parallel, each of the N parallel substream will modulate a separate carrier via the IFFT modulation block, which actually generates the OFDM symbol, performing the multicarrier modulation. The inter symbol interference and inter carrier interference are then dealt with by introducing a cyclic prefix. The cyclic prefix is obtained by copying the rear part of OFDM symbol and put it at the beginning of the symbol [8]. After Parallel to serial conversion, we can finally obtain the OFDM symbol [9]. At the receiver, the inverse operations are performed; starting with the removal of the cyclic prefix [10], the spectral decomposition of the received samples calculated using the FFT algorithm [15] and finally the demodulation [16], in the case of performing a channel estimation and additional stage is added to estimate the response of the transmission channel [17].
4. SYSTEM DESCRIPTION

4.1. Orthogonality

Consider the time limited complex signals \( \{e^{j2\pi f_k t}\}_{k=0}^{N-1} \) which represent the different subcarriers \( a_{f_k} = \frac{T}{T_{\text{sym}}} \) the OFDM signal, where \( 0 \leq t \leq T_{\text{sym}} \). The signals are defined to be orthogonal if the integral of the products on their common (fundamental) period is zero. The orthogonality described by (1) is the main condition characteristic of an ICI free OFDM signal.

\[
\frac{1}{T_{\text{sym}}} \int_0^{T_{\text{sym}}} e^{j2\pi f_k t} e^{-j2\pi f_i t} dt = \frac{1}{T_{\text{sym}}} \int_0^{T_{\text{sym}}} e^{j2\pi f_{k-i} T_{\text{sym}}} e^{-j2\pi T_{\text{sym}} t} dt = \begin{cases} 1, & \text{if } k = i \\ 0, & \text{otherwise} \end{cases} \tag{1}
\]

4.2. OFDM modulation and demodulation

OFDM transmitter codes the bit stream into a sequence of PSK symbols which will be subsequently parallelized into N streams. This conversion is carried out by different subcarriers. Let \( X_l[k] \) denote \( l^{th} \) transmit symbol at the \( k^{th} \) subcarrier, \( l = 0, 1, 2, ..., \infty \), \( k = 0, 1, 2, ..., N - 1 \). After the serial-to-parallel conversion, the duration of transmission time for \( N \) symbols becomes \( N T_s \), which forms a single OFDM symbol with a length of \( T_{\text{sym}} \) (i.e., \( T_{\text{sym}} = N T_s \)). Let \( \psi_{l,k}(t) \) be the \( l^{th} \) OFDM signal at the \( k^{th} \) subcarrier, which is given by:

\[
\psi_{l,k}(t) = \begin{cases} e^{j2\pi f_k (t - l T_{\text{sym}})} & \text{for } t \in [0, T_{\text{sym}}) \\ 0, & \text{otherwise} \end{cases} \tag{3}
\]

Then the pass band and baseband OFDM signals in the continuous-time domain can be expressed respectively as (4), (5).

\[
X_l(t) = Re \left\{ \frac{1}{T_{\text{sym}}} \sum_{k=0}^{N-1} X_l[k] \psi_{l,k}(t) \right\}, \text{ and} \tag{4}
\]

\[
X_1(t) = \sum_{l=0}^{N-1} \sum_{k=0}^{N-1} X_1[k] e^{j2\pi f_k (t - l T_{\text{sym}})} \tag{5}
\]

The sampling of the continuous time based OFDM signal given in (4) can be carried out at \( t = l T_{\text{sym}} + n T_s \) with \( T_s = \frac{T_{\text{sym}}}{N} \) and \( f_k = \frac{k}{T_{\text{sym}}} \) to yield the corresponding discrete-time OFDM symbol as (6).

\[
X_1[n] = \sum_{k=0}^{N-1} X_1[k] e^{j2\pi kn/N}, \text{ for } n = 0, 1, ..., N - 1 \tag{6}
\]

Note that (6) is the N-point IDFT of PSK data symbols \( x_1[k]_{k=0}^{N-1} \) is performed using the inverse fast Fourier transform (IFFT) algorithm. Considering the received baseband symbol \( y_1(t) = \sum_{k=0}^{N-1} X_1[k] e^{j2\pi f_k (t - l T_{\text{sym}})} \) \( \forall t \leq l T_s + n T_s \), the transmitted symbol \( X_1[k] \) can be reconstructed by the orthogonality among the subcarriers in (2) as:
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\[ Y_1[k] = \frac{1}{T_{\text{sym}}} \int_{-\infty}^{\infty} y_1(t) e^{-j2\pi f_k(t-kT_{\text{sym}})} dt \]
\[ = \frac{1}{T_{\text{sym}}} \sum_{i=0}^{N-1} X_1[i] e^{j2\pi f_i(t-iT_{\text{sym}})} e^{-2j\pi f_k(t-iT_{\text{sym}})} dt \]
\[ = \sum_{i=0}^{N-1} X_1[i] \frac{1}{T_{\text{sym}}} \int_{-\infty}^{\infty} e^{j2\pi (f_i-f_k)(t-iT_{\text{sym}})} dt \]
\[ = X_1[K] \quad \text{(7)} \]

where the effects of channel and noise are not considered. Let \( y_1[n]_{n=0}^{N-1} \) be the sample values of the received OFDM symbol \( y_1(t) \) at \( t = T_{\text{sym}} + nT_s \). Then, by integrating (7) in the modulation process the discrete time form of the signal is obtained:

\[ y_1[k] = \sum_{n=0}^{N-1} y_1[n] e^{-j2\pi kn/N} \]
\[ = \sum_{n=0}^{N-1} \left( \frac{1}{N} \sum_{i=0}^{N-1} X_1[i] e^{j2\pi iN/n} \right) e^{-j2\pi kn/N} \]
\[ = \frac{1}{N} \sum_{i=0}^{N-1} X_1[i] e^{j2\pi (i-k)n/N} \]
\[ = X_1[k] \quad \text{(8)} \]

As shown in (8) is the N-point DFT of \( y_1[n]_{n=0}^{N-1} \) which is computed by using the fast Fourier transform (FFT) algorithm. Diagram in Figure 4 depicts the OFDM modulation and demodulation structure, for \( N=6 \), the frequency domain symbol \( X[k] \) modulates the subcarrier with a frequency of \( f_k = kT_{\text{sym}} \), and at the other end of the reception the demodulation is performed by taking advantage of the orthogonally between subcarriers. The original symbol \( k \) has duration of \( T_s \), but its length has been extended to \( T_{\text{sym}} = NT_s \) by transmitting N symbols in a parallel form. Figure 4 illustrates a realization of orthogonally between all subcarriers.

**Figure 4. Block diagram of OFDM modulation and demodulation of 6 parallel streams**

5. **EFFECT OF MULTIPATH**

In the following section we present the expression of SINR as a function of the following parameters: symbol length [8], CP length [18], multipath and the thermal noise [16]. The CP length is \( \Delta \) seconds. The combined length of the OFDM symbol and the CP is \( T_G + NT_s \). The function \( C(\tau) \) is defined as (9). This is obtained by applying the C function defined in the equation and translated in time domain as in the spectrum given in Figure 5.
C(τ) = \begin{cases} 
0, & \tau < -N\tau_s \\
\frac{N\tau_s + \tau}{N\tau_s}, & -N\tau_s < \tau < 0 \\
1, & 0 < \tau < T_G \\
\frac{N\tau_s - (\tau - T_G)}{N\tau_s}, & T_G < \tau < N\tau_s + T_G \\
0, & N\tau_s + T_G < \tau 
\end{cases}
(9)

In the scenario of a N path channels with complex gains \( h(t) = \sum_{m=1}^{N\text{paths}} a_m \delta(t - \tau_m) \), the SINR for a channel with transmit signal power \( \sigma_n^2 \) per subcarrier and thermal noise of variance \( \sigma_n^2 \) per subcarrier, can be written in terms of signal and interference power.

\[
\text{SINR} = \frac{P_s}{\sum_{m=1}^{N\text{paths}} |a_m|^2 + \sigma_n^2 P_h}
(10)
\]

where:

\[
P_s = \sum_{m=1}^{N\text{paths}} C(\tau_m)^2 E|a_m|^2
(11)
\]

is the useful signal power after the FFT, and:

\[
P_t = \sum_{m=1}^{N\text{paths}} (1 - C(\tau_m)^2) E|a_m|^2 = P_h - P_s
(12)
\]

\( P_h = \sum_{m=1}^{N\text{paths}} E|a_m|^2 \) is the channel energy. We assume that all subcarriers are occupied, only then the expression is an approximation of the empirical ICI/ISI power, and useful power. For rays in the tapered portion of the bias function \( C(\tau) \leq \tau_m < N\tau_s + \Delta \), it can be shown that their interference contribution is:

\[
(1 - C(\tau_m)^2) E|a_m|^2 = \frac{(\tau_m - T_G)}{N\tau_s} \left[ 1 + \frac{N\tau_s - (\tau_m - T_G)}{N\tau_s} \right] E|a_m|^2
(13)
\]

In the middle term of this equation, the ‘1’ term is from ISI, while \( \frac{N\tau_s - (\tau_m - T_G)}{N\tau_s} \) term is due to ICI. For small excess delays, we can consider that the ICI term is approximately equal to the ISI term.

![Figure 5. The function C(\tau) applied to impulse response](image)

6. CYCLIC PREFIX

To add a cyclic prefix is to extend the OFDM symbol by copying the last samples of the OFDM symbol into its front [19]. Let \( T_G \) denote the length of CP in terms of samples [20]. Then, the extended OFDM symbols now have the duration of \( T_{\text{sym}} = T_{\text{sub}} + T_G \). Figure 6 shows two consecutive OFDM symbols [21], each of which has a CP of length \( T_G \) [22]. Figure 7 illustrates the ISI generated by the multipath effect on some subcarriers of the OFDM symbol [23]. It can be seen from this figure that if the length of the cyclic prefix (CP) exceeds the maximum delay of a multipath channel, the ISI effect of an OFDM symbol (dotted line) on the next may not affect the FFT of the next OFDM symbol, taken for the duration of \( T_{\text{sub}} \) [24]. This means that the guard interval must be longer than the maximum delay of the multipath channel in order to maintain the orthogonality with all other subcarriers over \( T_{\text{sub}} \), such that [25]:

\[
\frac{1}{T_{\text{sub}}} \int_{-T_{\text{sub}}}^{T_{\text{sub}}} e^{i2\pi k(t - \delta)} dt = 0, k \neq i
(14)
\]
For the first OFDM signal that arrives with a delay of $t_0$, and;

$$\frac{1}{T_{sub}} \int_{0}^{T_{sub}} e^{j2\pi f_k(t-t_0T_s)} \, dt = 0, k \neq i$$

(15)

For the second OFDM signal that arrives with a delay of $t_0 + T_s$.

7. SIMULATION AND DISCUSSION

7.1. Parameters of the simulation

To simulation setup details in MATLAB commercial software are shown in Table 1, the OFDM scheme has 128 sub-carriers using 16 QAM modulation, transmitted over the AWGN and Rayleigh channel, which depends on two parameters: $\tau$ and the gain on each path.

| Number of subcarriers | 128 |
|-----------------------|-----|
| Modulation scheme     | 16 QAM |
| Sampling period       | $1e^{-5}$ |
| CP length             | From 0% to 30% |
| Number of frames      | 1000 |
| The delay $\tau$      | 0, 100e$^{-5}$, 3.5e$^{-5}$, 1200e$^{-5}$ |
| The gains             | 0, -6, -3, -5 |

7.2. Simulation

In this work, we carried out a comparative study of the behavior of an OFDM transmission system, by varying the length of CP values from 0% to 30% of the total duration of the symbol. The metric used for this evaluation is the BER taking SNR values ranging from -5 to 20 dB. The AWGN channel considers only...
one path between the transmitter and the receiver and only a constant attenuation noise, so no multipath effect, which makes the transmission immune to ISI. The Rayleigh fading channel instead considers multipath between transmitter and receiver as shown in Figure 8. Therefore, the communication is affected by ISI, making its BER higher than that of the AWGN channel for different values of SNR.

The introduction of the CP as shown in Figure 9, reduces the BER of the signal on the Rayleigh fading channel while the one on AWGN channel remains unchanged. This is fully consistent with the fact that the AWGN channel does not take the multipath into account, so the introduction of the CP does not improve the BER for this channel. The Rayleigh fading channel response is more affected by the CP length, because the main parameters of this channel are the frequency spread spectrum and the delay introduced by the multipath. We clearly notice that their effect is reduced by the introduction of the CP, as shown on Figure 10 representing the BER Vs SNR for a signal without CP compared to another with a CP representing 0% to 30% from the inter symbol. We notice that keeping the signal at the same level 0.01 BER requires a 3 dB greater SNR or the introduction of 10% CP. The length of the CP needed to keep the signal at the same BER level is even more considerable when compared to the 30% CP length where we need a 6 dB SNR, in comparison to other simple solutions, this almost matches their performance allows the SNR to grow to 45 dB for the blind algorithm [15], and similar performance shown when using equalization [18].

![Figure 8. BER performance of OFDM system for AWGN and Rayleigh fading channel without CP](image1)

![Figure 9. BER performance of OFDM system for AWGN and Rayleigh fading channel with varying CP length](image2)

7.3. Constellation

In the constellation diagram for the 16 QAM modulation we depict the error introduced by the channel and caused mainly by the linear distortions (amplitude ripple, group delay, low carrier-to-noise ratio) as a dispersion of the symbol points around the theoretical position, for each point of the constellation. This degradation of the quality of the modulation is given by the MER shown in (15).

\[
MER = 10 \log_{10} \left[ \frac{\sum_{j=1}^{N} (i_j^2 + q_j^2)}{\sum_{j=1}^{N} (\delta i_j^2 + \delta q_j^2)} \right]
\]  

(16)

Assuming that the transmitted data-symbol is represented by the coordinate pair \((a_k + b_k)\). After reception, the baseband I, Q signals are given by:

\[
I_k = \text{Real}[ (a_k + j b_k) e^{j \phi_n} ]
= a_k \cos(\phi_n) - b_k \sin(\phi_n) + n_i
\]

\[
Q_k = \text{Imag}[ (a_k + j b_k) e^{j \phi_n} ]
= a_k \sin(\phi_n) + b_k \cos(\phi_n) + n_Q
\]  

(17)

In the Figure 10, for the same snr value the CP length can improve the quality of the MER hence the quality of the transmission, by limiting this dispersion, and for a lower value of the SNR, the effect of the CP length is more noticeable.
8. CONCLUSION

In this work, we have discussed the transmission problems in the OFDM transmission scheme, the effect of CP length has been simulated in terms of BER for AGWN and Rayleigh fading channel. The AWGN channel considers only one path between the transmitter and receiver, whereas the Rayleigh fading channel takes into consideration the multipath which is the main reason of the received signal distortion leading to the ISI. In OFDM system this is avoided by the introduction of the CP. On the simulation we carried out, we observed that the effect of the multipath decreases with the increasing of the CP length. It would be easy to assume that the increase of the CP length has always a positive impact on the transmitted signal, but because the duration of the CP is deducted from the total time dedicated to the data, a trade-off must be made between the robustness of the signal and the throughput, therefore, there are limits to the size of the CP. On the other hand, we carried a simulation on the effect of the CP on the dispersion of the constellation in the Rayleigh channel scenario and it yields that the introduction of the CP could reduce it considerably.

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