Performance Analysis of an Optical OFDM System
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Abstract: Orthogonal frequency division multiplexing (OFDM) is a modulation technique which is now used in most new and emerging broadband wired and wireless communication systems because it is an effective solution to intersymbol interference caused by a dispersive channel. Optical OFDM is proposed in two forms, one using direct-detection and the other using coherent detection. The main drawbacks of OFDM are its high peak to average power ratio and its sensitivity to phase noise and frequency offset. The aspire is to develop an efficient Optical OFDM system with the reduced peak to average ratio. The system will be less sensitive to phase noise and frequency offset. In this project, we describe the complete design of OFDM system. By observing the effects of changing the parameters of system, we try to reduce the drawbacks.

Key Words: Modulation, OFDM, Optical communication, OptSim.

1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is used extensively in broadband wired and wireless communication systems because it is an effective solution to inter-symbol interference (ISI) caused by a dispersive channel [3]. This becomes increasingly important as data rates increase to the point where, when conventional serial modulation schemes like quadrature amplitude modulation (QAM) or NRZ are used, the received signal at any time depends on multiple transmitted symbols [1]. In this case the complexity of equalization in serial schemes which use time domain equalization rises rapidly. In contrast, the complexity of OFDM, and of systems using serial modulation and frequency domain equalization, scale well as data rates and dispersion increase. A second major advantage of OFDM is that it transfers the complexity of transmitters and receivers from the analog to the digital domain. For example, while the precise design of analog filters can have a major impact on the performance of serial modulation systems, in OFDM any phase variation with frequency can be corrected at little or no cost in the digital parts of the receiver [2].

In OFDM system, data is transmitted in parallel on a number of different frequencies, and as a result the symbol period is much longer than for a serial system with the same total data rate. Because the symbol period is longer, ISI affects at most one symbol, and equalization is simplified. In most OFDM implementations any residual ISI is removed by using a form of guard interval called a cyclic prefix.

When frequency division multiplexing (FDM) is used in conventional wireless systems, or wavelength division multiplexing (WDM) is used in optical systems, information is also transmitted on a number of different frequencies simultaneously. However there are a number of differences between OFDM and these conventional systems:

- In OFDM the subcarrier frequencies are chosen so that the signals are mathematically orthogonal over one OFDM symbol period.
- Both modulation and multiplexing are achieved digit inverse fast Fourier transform (IFFT) and as a result, the required orthogonal signals can be generated precisely and in a very computationally efficient way.

In FDM/WDM there are frequency guard bands between the subcarriers. At the receiver the individual subcarriers are recovered using analog filtering techniques. In OFDM the spectra of individual subcarriers overlap, but because of the orthogonality property, as long as the channel is linear, the subcarriers can be demodulated without interference and without the need for analog filtering to separate the received subcarriers. Demodulation and demultiplexing is performed by a fast Fourier transform (FFT). The spectrum of an individual OFDM subcarrier has a form, so each OFDM subcarrier has significant side lobes over a frequency range which includes many other subcarriers. The resilience of OFDM to frequency-selective effects has been shown in [3] to permit the use of inexpensive multimode fiber in OFDM systems. An optical unequal-slot based sub channel allocation algorithm is used to maximize the total data rate in multiuser OFDMA system [6].
This paper presents an application of OFDM in optical communication. Section II outlines a typical OFDM system for wireless applications. In section III the application of OFDM to optical communication is discussed. In section IV conclusion is presented.

2. BASIC OFDM SYSTEM

A typical OFDM system for wireless applications is described in this chapter. Fig. 1 shows the block diagram of typical wireless OFDM system. The signals at various points and function of each block are described in the following point.

2.1 Coding Interleaving and Mapping

The first blocks in the transmitter are interleaving and coding. All OFDM systems use some form of error correction or detection because, if there is frequency selective fading in the channel, some of the parallel data streams will experience deep fading. The coding is usually preceded by interleaving because; a number of adjacent OFDM subcarriers may fall within the frequencies which are experiencing fading. In most broadcast applications of OFDM such as digital audio broadcasting (DAB) and digital video broadcasting (DVB) there are two layers of interleaving and coding so that a very low overall bit error rate (BER) can be achieved even over a very noisy channel. After coding, the data is mapped onto complex numbers representing the QAM constellation being used for transmission. Constellation sizes from 4 QAM to 64 QAM are typically used. While phase shift keying (PSK) is compatible with OFDM, it is rarely used. PSK in OFDM, unlike PSK in single carrier systems, does not have a constant signal envelope and, for large constellations, has smaller distance between constellation points and so is more susceptible to noise. The sequence of complex numbers output from the constellation mapping are then serial-to-parallel (S/P) converted to form a vector suitable for input to the IFFT.

![Figure 1. Block diagram of an OFDM transmitter and receiver.](image-url)
2.2 FFT and IFFT

The IFFT block is the main component in the transmitter and the FFT in the receiver. These are the functions which distinguish OFDM from single carrier systems. The input to the IFFT is the complex vector \( X = [X_0 \ X_1 \ldots \ X_{N-1}]^T \). The vector has length where \( N \) is the size of the IFFT. Each of the elements of \( X \) represents the data to be carried on the corresponding subcarrier. Usually QAM modulation is used in OFDM, so each of the elements of \( X \) is a complex number representing a particular QAM constellation point.

The upper case letters represent frequency or discrete frequency domain variables, and lower case for time domain. The output of IFFT is a complex vector \( x = [x_0 \ x_1 \ldots \ x_{N-1}]^T \). The main advantage in using FFT/IFFT is that the discrete signals at the input and the output of the transform for each symbol have the same total energy and same average power. The signals at the input and the output of the IFFT are for 4 QAM modulation and \( N = 16 \). The input to the IFFT is a vector of random values from the 4QAM constellation \( \{1 + j, 1 - j, -1 + j, -1 - j\} \). The output is the corresponding time domain vector \( x \). For \( N \geq 64 \) the real and imaginary components of an OFDM time domain signal are approximately Gaussian. For wireless OFDM systems which have already been standardized, values of \( N \) ranging from 64 in wireless LAN systems to 8096 in digital television systems have been used.

At the receiver the FFT performs a forward transform on the received sampled data for each symbol. The vector representing the sampled time domain signal at the input to the receiver FFT is \( y = [y_0 \ y_1 \ y_2 \ldots \ y_{N-1}]^T \), and the discrete frequency domain vector at the FFT output is \( Y = [y_0 \ y_1 \ y_2 \ldots \ y_{N-1}]^T \). \( N \) is the samples are required per OFDM symbol (excluding CP).

2.3 Sequences of Symbols and Cyclic Prefix

The IFFT generates each OFDM symbol. The transmitted signal consists of a sequence of these OFDM symbols. To denote different OFDM symbols when a sequence of symbols rather than a single symbol is being considered we need to extend the notation to include a time index. Let \( x(i) = [x_0(i) \ x_1(i) \ldots \ x_{N-1}(i)]^T \) be the output of IFFT in the \( i^{th} \) symbol period. In most OFDM systems, a CP is added to the start of each time domain OFDM symbol before transmission. In other words a number of samples from the end of the symbol is appended to the start of the symbol. So instead of transmitting \( x(i) = [x_0(i) \ x_1(i) \ldots \ x_{N-1}(i)]^T \) the sequence \( xCP(i) = [x_{N-1}(i) \ldots x_0(i), x_0(i) \ldots \ x_{N-1}(i)]^T \) is transmitted; where is the length of the cyclic prefix.

When a CP is used, any distortion caused by a linear dispersive channel can be corrected simply using a ‘single-tap’ equalizer. For the case where OFDM transmission is at pass band, the gains and the signals will be complex; for the case of baseband transmission the gains and signals are real. As long as the start of the receiver time window is aligned with the start of the “main” OFDM symbol of the first arriving signal, and if the delay spread is less than the length of the CP, there is no intersymbol interference. The signal received in the \( i^{th} \) time window depends only on the \( i^{th} \) transmitted symbol.
2.4 Transmitter and Receiver Front End

Fig. 1 shows a block combining filtering, parallel-to-serial conversion (P/S) and digital-to-analog conversion (D/A) because in practice there is some choice about the order of these processes. For example, OFDM symbols are often windowed (a form of time variant filtering) to reduce the side lobes, sometimes the digital signal is up sampled before D/A conversion to simplify the analog filtering, and filtering can be in the analog or digital domain. However after this process the signal $x(t)$ is an approximately band limited signal consisting of sinusoids of the baseband subcarrier frequencies. In wireless OFDM systems $x(t)$ is a complex signal which forms the input to an IQ modulator for up conversion to the carrier frequency. For an OFDM system to work successfully the system must be linear between the transmitter IFFT input and the receiver FFT output. writers is [7].

3. OFDM MODEL

OFDM has recently used in optical communication. There are many differences in conventional OFDM systems and optical OFDM systems. Table 1 summarizes theses differences.

Table 1: COMPARISON OF TYPICAL OFDM SYSTEM AND TYPICAL OPTICAL SYSTEM

<table>
<thead>
<tr>
<th>Typical OFDM System</th>
<th>Bipolar</th>
<th>Information carried on electrical form</th>
<th>Local oscillator at receiver</th>
<th>Coherent Reception</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Optical System</td>
<td>Unipolar</td>
<td>Information carried on optical intensity</td>
<td>No local oscillator (laser) at receiver</td>
<td>Direct Detection</td>
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</table>

In this project we are going to analyze the performance of an OFDM system for optical communication by using OptSim. Orthogonal frequency division multiplexing (OFDM) modulation uses orthogonal carriers to transport the phase and amplitude information of multiple low-rate bit sequences modulated using BPSK, QPSK or QAM. Serial-to-parallel and parallel-to-serial conversions enable to transmit and receive a single high-rate bit stream.

The OptSim OFDM modulation models are several discrete blocks that can be combined at will with filters and noise sources to simulate realistic OFDM system setups. Moreover the signal can be monitored at each stage of the modulation process, making them ideal to study the modulation behavior details.

OptSim includes convenient OFDM transmitter and receiver Compound Components available in the Sample-Mode_Compound_Components Transmitters and Receivers categories. These CCs are used in the OFDM radio-over fiber using amplitude modulation OFDM_ROF_AM.moml and phase modulation OFDM_ROF_PM.moml. On the other hand the OFDM_back2back.moml use a single level not hierarchical design with several signal measurement components to show the principia behind OFDM modulation and the building blocks of OFDM transmitters and receivers.

Figure 3. OFDM Model.
Fig. 3 shows an OFDM system using phase modulation named OFDM_ROF_PM.moml. In the transmitter, a single 10 Gbit/s pseudo-random bit sequence is converted into a number of lower rate bit sequences controlled by the symbol QAM_bit_number. In fact the multiplicity of the serial-to-parallel conversion corresponds to the number of bits to encode one QAM symbol. An intermediate binary to Gray-code conversion is used in the modulation process.

QAM constellations are obtained at QAM modulator. Here 4-QAM is used. Next the model IFFT_OFDM converts the QAM symbols in OFDM symbols with an IFFT operation using a number of subcarriers controlled by the symbol subcarriers_number, both accepting in input and returning on output baseband in-phase and in-quadrature signals. Fig. 4. Shows the power spectrum at the output of the OFDM transmitter obtained with the component probe3.

Fig. 4(a) and 4(b) shows optical spectra of baseband signal for CP = 0.25 and CP = 0. When there is no CP the spectra comes as shown in 4(b). The CP results in band spectrum. Here no windowing is used, so the first side lobe of an OFDM spectrum is 13 dB below the in-band power. The rate with which the out-of-band power falls off depends on the number of subcarriers. So for DVB systems, where the FFT size is 2048 or 8196, the spectrum falls of very rapidly, but for wireless LANs, where, the out-of-band power would create problems, so time domain windowing or filtering is used to reduce the side lobes.

After phase modulator fiber is connected. On the receiver side, before the signal is given to optical interferometer first. It converts the phase deviation in amplitude deviation to be detected with photo detector. The RF signal is translated to baseband with a quadrature mixing down conversion. The replica at twice the carrier frequency originated by the down conversion process is filtered out using two 7-pole low-pass Bessel filters centered at the carrier frequency, 10 GHz in this example. Finally the model FFT_OFDM extracts the transmitted QAM symbols from the OFDM signal at baseband with an FFT operation. The OFDM modulation is very sensitive to the sampling instant at the receiver. Not sampling the OFDM symbol at the optimum sampling instant results in very fast deterioration of the system performance. For this reason the OptSim models IFFT_OFDM and FFT_OFDM include the option to use a training sequence to automatically find the optimum sampling instant. Moreover the model FFT_OFDM can also automatically recover the amplitude and phase of the original QAM symbols, thus facilitating the demodulation into bit streams of the received QAM signal. Fig. 5 shows the in-phase component of the OFDM signal at scope_I connected to the output. Fig. 6 shows the received QAM constellation with controlling automatic synchronization and amplitude/gain recovery. Finally the received QAM symbols are converted into low-rate parallel bit streams and into a single high-rate bit sequence with a parallel-to-serial conversion.

![Sim OFDM ROF PM Optical Spectrum at 054840, probe1, Run 1](image1)

![Sim OFDM ROF PM OptX:Optical Spectrum at 057480, probe3, Run 1](image2)

Figure 4. Power spectrum of transmitted OFDM signal at probe3 (a) for CP = 0.25, (b) for CP = 0
The system uses 4-QAM with cyclic prefix of 0.25. At the transmitter side laser (1550nm wavelength) is used and on the receiver side PIN diode of 1550 nm wavelength is used. System is applied for 3km length. OFDM can be built using 64-QAM, 128-QAM and the results can be observed. Also the constraints can be done for long haul communication.
4. CONCLUSION
In this paper, the theoretical fundamentals for OFDM are reviewed first. A typical OFDM transmitter and receiver are described and the roles of the main signal processing blocks explained. The time and frequency domain signals at various points in the system are described. An application of OFDM in optical communication is proposed. It is shown that if a cyclic prefix is added to each OFDM symbol, any linear distortion introduced by the channel can be equalized. The proposed device is for 3km length. As the length of fiber increases the distortion gets added to it. It is showed that the receiver-based digital signal processing to mitigate self-phase modulation.

5. ACKNOWLEDGEMENT
We would like to thank the RSoft team for their technical support and guidance.

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