OFDM PERFORMANCE ON AERONAUTICAL CHANNELS

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ABSTRACT

This paper provides an introduction to the Orthogonal Frequency Division Multiplexing (OFDM) scheme which has been proposed for future aeronautical telemetry applications. OFDM offers the potential for high data rates on radio channels with multipath such as aeronautical telemetry channels. This paper provides in introduction to OFDM and demonstrates how orthogonality is maintained over multipath channels by the introduction of a guard band and by the inclusion of a cyclic prefix. The simulation of OFDM in multipath is simulated and performance results are presented that show the degradation of this scheme on a multipath channel with and without the guard band and the cyclic prefix.

Key Words: OFDM, Multipath, Inter-Symbol Interference, Inter-Channel Interference, Aeronautical Channel, Orthogonal

INTRODUCTION

Frequency Division Multiplexing (FDM) is a discrete multi-tone data transmission scheme where the data is spread over multiple sub-frequencies within a frequency band. OFDM therefore increases the rate of transmission of the medium by a factor equal to the number of the subchannels. Its spectral efficiency, robustness against Inter-Symbol-Interference and fading are just some of the properties that make OFDM an ideal choice for the physical layer of the proposed iNET enhanced network architecture. This proposed network will succeed IRIG 106 standard and will support bi-directional communication between test articles and the ground station while offering remarkable quality of service (QoS) amongst other advantages. This technology is applicable in both wireless networks and physical media.

FREQUENCY DIVISION

Frequency Division in OFDM scheme means that the transmission line or channel is divided into multiple subchannels, which are non-overlapping, and therefore cannot interfere with each other. As a result, they can be individually assigned symbols (groups of data bits) intended to be relayed through the channel. **Multiplexing**, on the other hand is the process of combining the subchannels and sending them though the same medium simultaneously. In order to ensure that the subchannels, also known as subcarriers, do not interfere destructively with each other during data relay, they have to be orthogonal to each other. In the case of a wireless network, for instance, the carrier signal is an electromagnetic wave, which is split into constituent sine waves. These constituent waves are infinitely many, each differing from each other by its polar orientation or spacing. As a result, these different polar orientations (spacing) cause some degree of interference between the waves. This interference, also referred to as Inter-Channel-Interference (ICI) occurs when the waves are not orthogonal. After this channel subdivision, orthogonal waves, which are also parallel to each other, are carefully isolated and used as data carriers or subchannels. This allows for an enormous amount of data symbols to be transmitted over the channel. This technique also prevents the receiver (with a demodulator) from seeing signals that are different from the intended subcarriers. A typical structure of two orthogonal subcarriers looks similar to the figure 1 below:-

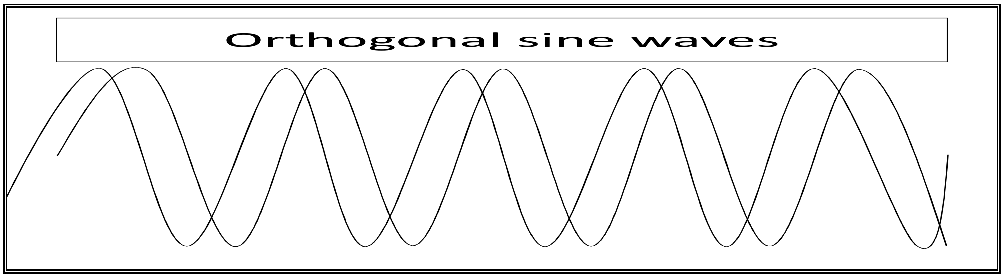
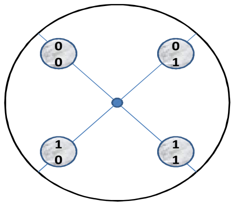


Figure 1: Orthogonal Sine waves. *The waves are spaced 90 degrees apart so that their trigonometric properties are completely distinct.*

OFDM offers a set of advantages that have made it desirable to some of the largest telecommunication and ISP companies like Qualcomm (Flarion Technologies), Lospan Wireless (MIMO-OFDM), Cisco Systems (Vector-OFDM) and Lucent/Bell Labs (flash-OFDM). Each of these companies utilize from a variety, some of the communications protocols including Bluetooth (for PDAs, laptops and cell phones) and cellular like CDMA, TDMA and GSM. Among the most significant advantages of OFDM is its spectral efficiency. Large amounts of data symbols are transmitted simultaneously over one transmission medium which arise from the channel subdivision. This is achieved by applying a modulation scheme that can fit as much data into the sub-channels as possible, maximizing power efficiency, spectrum efficiency and data rate.

In the initial stage of the transmission, **Phase Shift Key** (PSK) modulation scheme is preferably used in modulating binary data bits into symbols, which are then inserted into the sub-channels. For instance, one symbol may contain four data bits, which are treated the same a one data bit. Phase shifting is preferred especially because it is more energy efficient compared to amplitude shifting or frequency shifting. The PSK scheme takes a discrete number of wave phases; each representing a unique sequence of bits and sends them over the link as though they were a single unit of data. There are several sub-schemes including **Binary Phase Shift Key** (BPSK) scheme which uses two phases to encode data bits into symbols and **Quadrature Phase Shift Key** (QPSK) scheme which takes four phases at a time. An increased efficiency is achieved when QPSK scheme is applied. It encodes two bits per symbol, which is twice that achieved in using BPSK. In essence, it uses a four phases that are perpendicular to each other and encodes the bits into the phases at equidistant points. The constellation diagram shown in Fig. 2 below can be assumed to be a transverse section of the channel in which QPSK scheme is used. It represents the PSK symbols in a complex plane. This can be expanded with Quadrature Amplitude Modulation (QAM) which can provide as much as 10 bits per symbol. However, a high error rate will be recorded at the receiver due to the Inter-Symbol and Inter-Channel interferences that occur as a result of **multipath**.

QUADRATURE PHASE SHIFT KEY

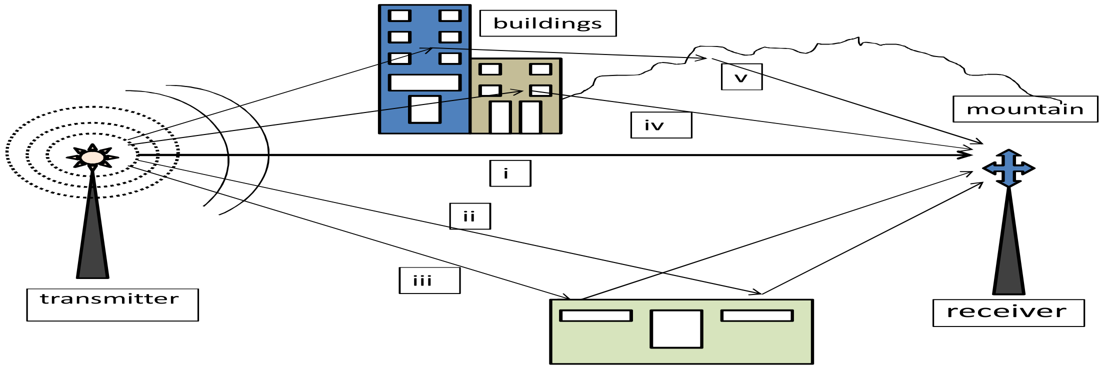


Constellation Diagram with Grey coding.
Each of the four perpendicular phases is coded with two bits at equidistant points.

Figure 2: Constellation diagram with Grey's coding.

MULTIPATH

This is a term used to describe the various paths that the signal takes to travel from the transmitter to the receiver. A radio frequency traveling from the sending antenna towards the receiver in the form of a radial wave spreads out radially around that sending antenna. The further away it travels from this antenna, the wider it disperses. It thus encounters obstacles along its path that cause interferences such as reflection, refraction, and diffraction. These interferences subject the signal to be distorted. Obstacles in this case can include buildings, hills, vegetation, rugged terrains, layers of the ionosphere and even water masses. Since these obstacles are placed at different distances along the path of the signal and also have infinite variations in form, they cause infinitely many reflected images of the original wave form. More so, they cause different amounts of delay on each of the reflected wave fronts, causing them to arrive at the receiver at different times as illustrated in figure 3 below:-



Path (i) illustrates the signal travelling along the line of sight while ii, iii, iv and v represent reflected paths.

Figure 3: Multipath.

From this illustration, we see that the signal can travel in a straight line between the two antennae, but only when there is no obstacle in between. This line is referred to as the **line of sight.** A signal that arrives at the receiver along this line is normally the strongest, and consequently gives the biggest impulse response at the receiver. All other duplicates of the same signal that follow alternative paths due to reflection are weaker. The delay that a reflected signal encounters differs according to the total length of the path that it follows. It may be reflected once or a number of times depending on the nature of the path it takes. In fact, more obstacles cause more delay.

INTER-SYMBOL INTERFERENCE (ISI)

Inter-Symbol Interference (ISI) is another effect that arises from multipath. ISI is a destructive interference whereby a reflected ghost image affects the direct line of sight signal at the receiver. Ghost images of the original signal arrive at the receiver with variable delays, therefore distorting the line-of-sight signal. They add up on the amplitude of the line-of-sight signal and change its form causing disarrangement of data symbols. Consequently, the demodulator records errors. Figure 4 below is a simplified illustration showing how delayed signals interfere with the line-of-sight signal.

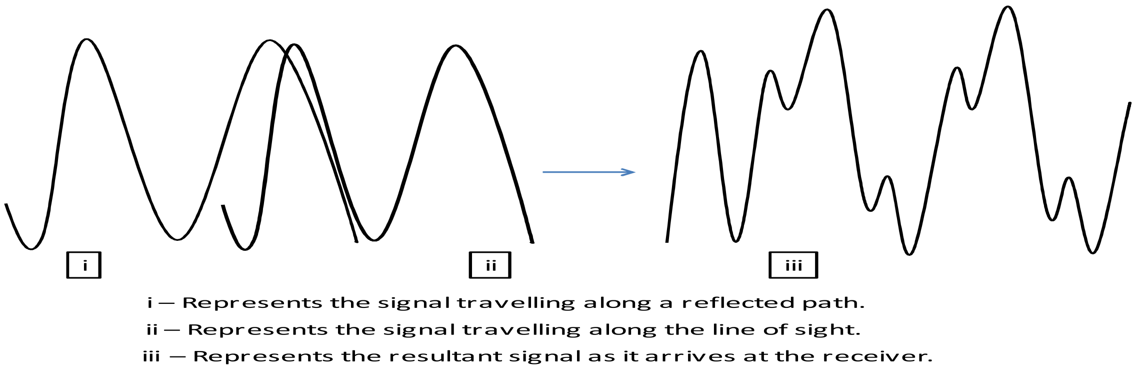


Figure 4: Effect of reflection and delay on a symbol stream.

Bleeding also occurs at this time. This is the interference of a ghost image of an initially sent symbol stream onto a later sent stream. To demonstrate bleeding, a series of rectangular blocks representing symbol streams are used in figure 5 below.

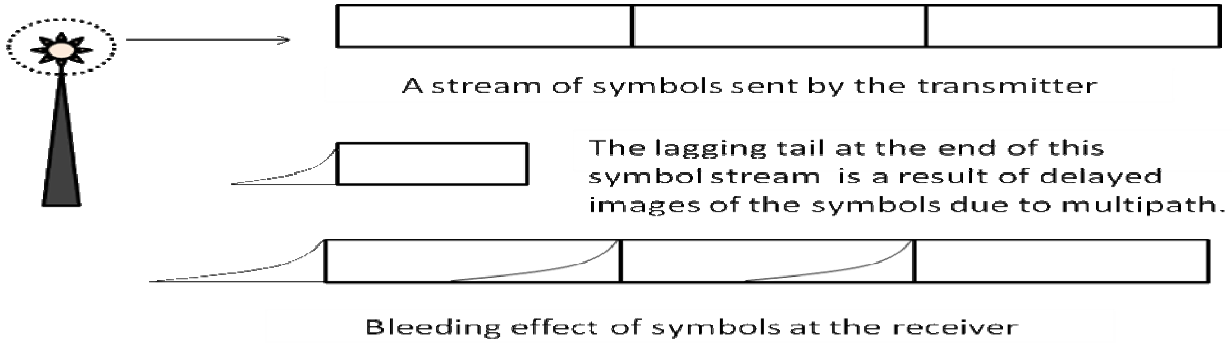


Figure 5: Bleeding effect causing inter-symbol interference

From the diagram, it is clear that the symbol stream at the receiver is not the same as it was transmitted. The receiver sees symbols that have been bled into and distorted. In order to avoid this distortion, a space is created between every two serially arranged symbol streams. This empty space is called the **guard band.**

INTER-CHANNEL INTERFERENCE (ICI)

Inter-Channel Interference is another problem that occurs in the OFDM transmission. This results from lack of orthogonality of the subcarriers. Carrier frequencies can sometimes lose their orthogonality during time-frequency conversions of the data symbols. In order to convert the binary-coded symbols from time domain to frequency domain, the **inverse Fast Fourier Transform (iFFT)** conversion scheme is used. This scheme is preferred especially due to its simplicity and high efficiency. Using iFFT, each subcarrier is modulated with a rectangular pulse. However, the frequency response of the channel naturally attenuates some frequencies more than others, causing them to lose orthogonality. At such a time, the attenuated subcarriers no longer possess completely distinct trigonometric properties relative to their phase and position at every point because their sine functions have been changed by some different amounts. More so, the inner product of their sinusoids (basic vectors) is no longer zero and hence not orthogonal. This non-orthogonality allows the subcarriers some degree of similarity, and thus they 'interact' with each other exchanging energy. This interaction prevents the unique recovery of the correct spectral coefficients of the sinusoids when a **direct Fourier Transform (FFT)** is performed at the demodulator. This interference can be corrected by **padding** the data symbols.

ISI causes a high error rate as shown in figure 6 below. The graph compares the **Energy per bit to Noise Power spectral density ratio (Eb/No)** - which is simply a normalized measure of the **Signal to Noise Ratio (SNR)**, to the **Error Ratio (ER)**

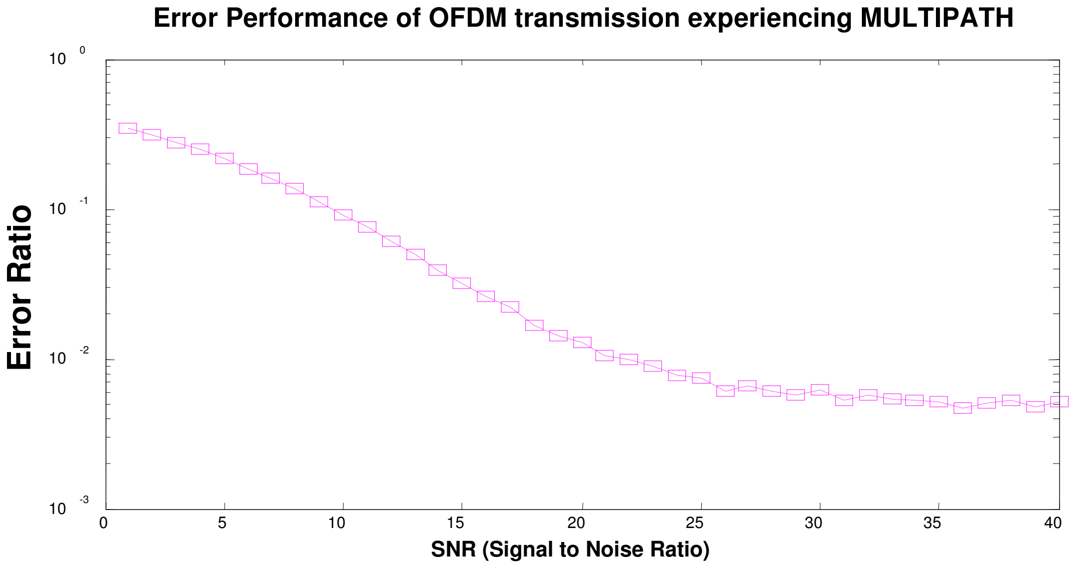


Figure 6: performance of a link experiencing multipath.

This graph shows an error rate of 10^{-2} at best, which means that one in a hundred symbols will contain errors. This is a very poor performance compared to the theoretical performance that would be achieved in an ideal path with no effect of multipath. It would have a reduced error rate to nearly 10^{-5} before any equalization is required. This severity of error requires corrective action. The first measure, therefore, is the creation of guard bands or guard intervals.

GUARD BANDS (GUARD INTERVALS)

First, guard intervals or guard bands are created. These, as mentioned earlier, are empty spaces between two adjacent, serially arranged symbol streams. The guard band serves as a delay between the two symbol streams so that the delayed images of an initially sent stream will land within the guard interval at the receiver. The size of the guard band is selected so that all the bleeding occurs within the band. A short guard band would fail to correct the interference because bleeding would occur beyond the length of the band and interfere with other arriving streams. On the other hand, an unnecessarily long guard band would cause inefficiencies in the transmission.

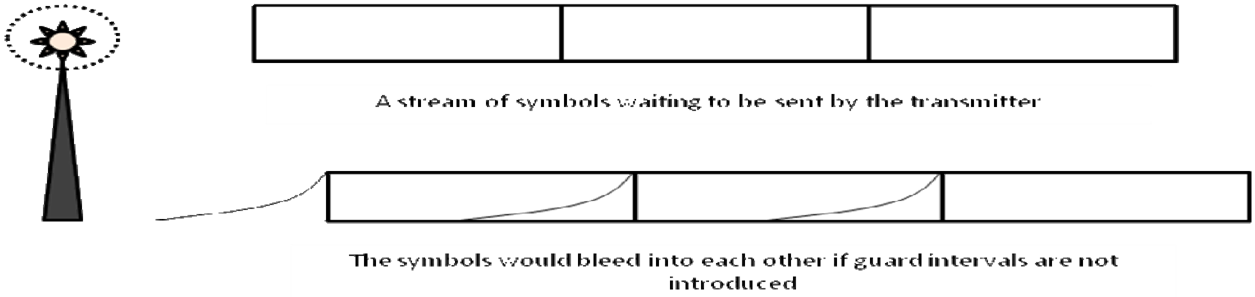


Figure 7: Bleeding effect.

On introducing guard bands of the right size, bleeding occurs only inside the bands. The destructive effect therefore does not affect the incoming data streams.

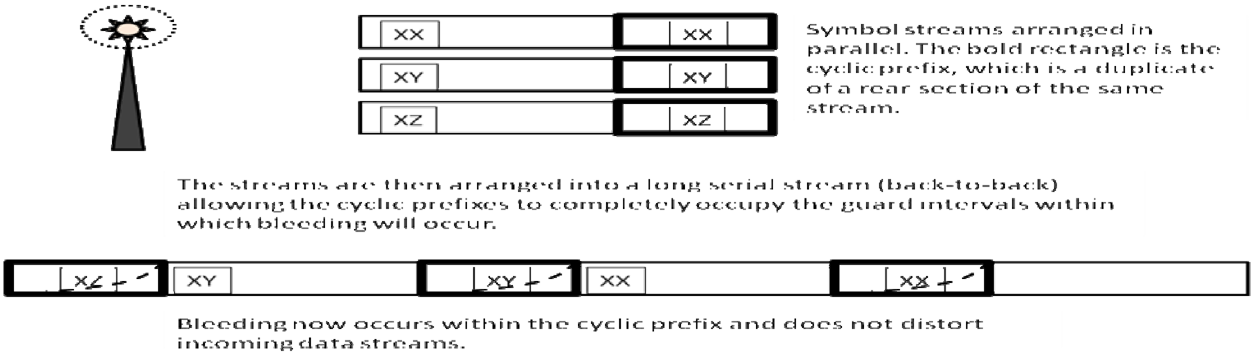
Figure 8: Bleeding within the guard bands (Guard intervals).

Clearly, guard intervals reduce Inter-Symbol Interference significantly. In fact, the error rate in a link with guard bands used reduces to up to less than 10^{-3} at an SNR of 40dB as seen in figure 12a below.

Although this improvement appears quite good, there is still a big difference between this performance and the ideal-path performance which is the ultimate target. Therefore, the link requires further modification. Equalization at this point would be quite effective, but also quite expensive. A more appropriate technique that requires less energy and at the same time improves the channel's performance is used. The most efficient corrective method is **cyclic prefixing.**

CYCLIC PREFIXING

This is simply the duplication of some rear segment of a stream of data symbols and appending the duplicate segment at the front end of the same stream. The prefix is inserted to completely occupy the guard band, therefore linking two symbol streams. Prefixing is done before the data streams are converted from parallel to serial arrangement.



Symbol streams arranged in parallel. The bold rectangle is the cyclic prefix, which is a duplicate of a rear section of the same stream.

The streams are then arranged into a long serial stream (back-to-back) allowing the cyclic prefixes to completely occupy the guard intervals within which bleeding will occur.

Bleeding now occurs within the cyclic prefix and does not distort incoming data streams.

Figure 9: Cyclic prefix correcting inter-symbol interference.

In figure 11 the smaller, bold rectangles represent cyclic prefixes that have been bled into, while the longer rectangles represent the uninterrupted information as it arrives at the receiver. The demodulator at the receiver then discards the cyclic prefixes, making it possible to recover the undistorted information, which is then rearranged back to a parallel series and decoded. It is important to remember that cyclic prefixes are redundant data being sent across the link, and will not be needed after the information has been demodulated. A cyclic prefix of the right size is the most effective, as well as efficient. A performance curve of a link in which cyclic prefixing has been done yields the performance shown in figure 10b below.

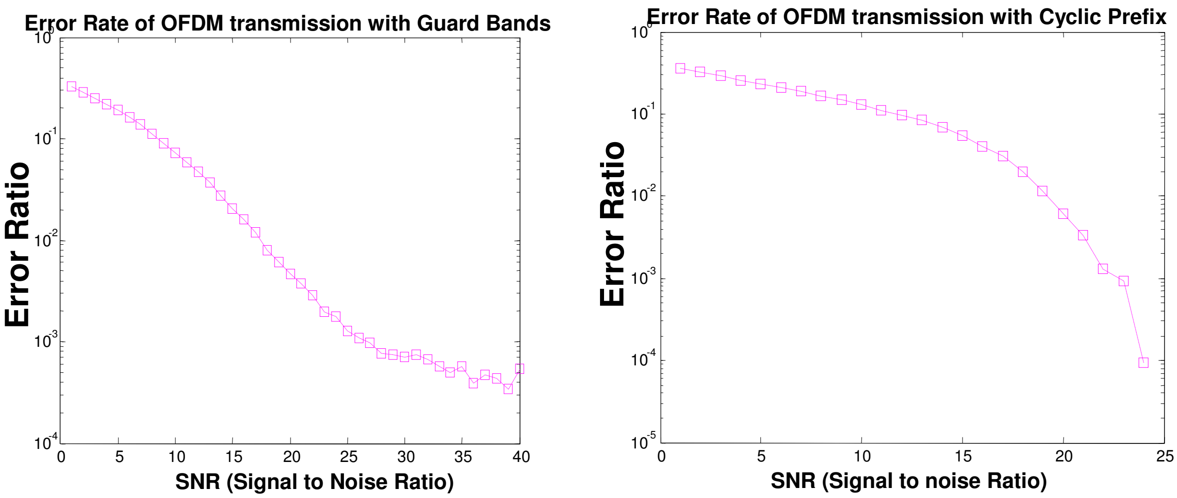


Figure 10a

Figure 10b

Figure 10a illustrates OFDM performance with guard bands while 10b illustrates the improvement after cyclic prefixing.

At best, this graph indicates a performance of error rate less than 10^{-4} at an SNR of under only 25 decibels. This is a quite attractive performance, considering that the link suffers a moderately severe effect of multipath, and no equalization has been applied so far. This achievement demonstrates the significant difference between a link with cyclic prefixing, another with guard bands only and one without any corrective measures. These differences can be seen in the composite figure 13 below:-

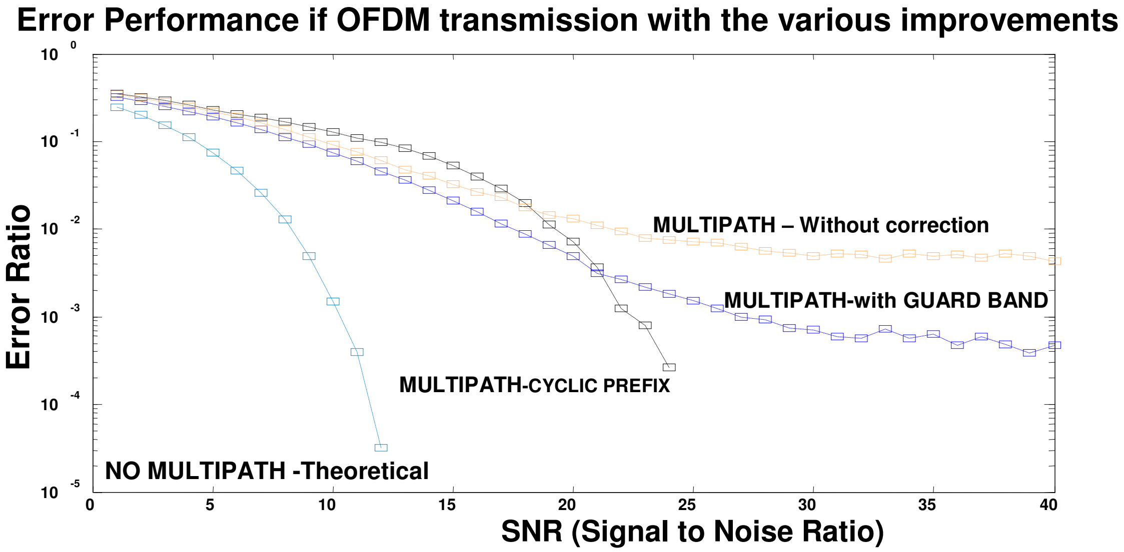


Figure 11: Composite plots showing the performance of the same link at every step of improvement.

Cyclic Prefixing achieves almost the same error rate as the ideal curve, except that the transmitting energy per bit (Eb/No) for cyclic prefix is about 25dB while that the ideal path is about 12dB. This however is a significant achievement, and makes it reasonable to introduce equalization techniques at this stage.

CONCLUSION

This paper has demonstrated the performance advantages of OFDM. It shows that OFDM is severely degraded by the introduction of multipath channels due to inter-symbol and inter-channel interference. These effects can be reduced by the introduction of a guard band between data symbols and by the inclusion of a cyclic prefix. By doing so, the error performance can be reduced from 10^{-2} to 10^{-4}, two orders of magnitude. Further improvements in performance will require channel equalization.

Acknowledgments

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