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Performance Evaluation of OFDM in Underwater Acoustic Communication

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Abstract

Communicating at a high data rate in underwater channel is challenging. Such communications must be acoustic in order to travel long distances. The underwater acoustic channel has a long delay spread, which makes orthogonal frequency division multiplexing (OFDM) an attractive communication scheme. However, the underwater acoustic channel is highly dynamic, which has the potential to introduce significant multipath. OFDM has proved to be an effective technique for combating the multipath delay spread without the need for complex time-domain equalizers. This paper explores a number of means for mitigating multipath in underwater communication systems.

1. Introduction

Underwater communication first introduced during world war II especially for military needs, underwater communications today have a growing need in a number of civil and commercial applications like remote control in off-shore oil industry, monitoring pollution in environmental systems, efficient collection of scientific data recorded at stations located at sea bed, communication among divers as well as underwater vehicles and mapping of the sea bed for detecting objects as well as for the discovering new resources. Unfortunately, radio frequency (RF) electromagnetic waves propagate over long distances through conductive salty water only at extra low frequencies (30−300Hz). Optical electromagnetic waves do not suffer from such high attenuation, but are affected by scattering and require high precision in pointing laser beams. Underwater optical communications have therefore ranges of a few tens of meters only and are typically directional. Acoustic communication is therefore the transmission technology of choice for underwater communication systems [1] as shown in table 1. Still, due to the physical properties of the propagation medium, underwater acoustic signals suffer from severe transmission loss, time-varying multipath propagation, Doppler spread, limited and distance-dependent bandwidth, and high propagation delay. For example, the slow propagation speed of sound underwater makes Doppler a significant effect when signals are scattered from moving ocean wave surfaces and from mobile vehicles. These formidable challenges limit the available bandwidth for underwater acoustic communications, while the rapidly varying channel causes communication links to be highly unreliable, ultimately hindering advancement in underwater communications. But on the other hand, data transmission rate required for UAC applications is continuously surging with the arrival of high resolution signals. Underwater communications in general mainly gets affected due to:

1) *Channel Variations*
   a) Temperature
   b) Salinity of water
   c) pH of water
   d) Depth of water or pressure
   e) Surface/bottom roughness.

2) *Noise*

   Acoustic noise in underwater communication channel can be either natural ambient noise or Man-made noise. The latter is mainly caused by machinery noise (pumps, reduction gears, power plants, etc.), and shipping activity (hull fouling, animal life on hull, cavitation), especially in areas encumbered with heavy vessel traffic, while the former is related to hydrodynamics (movement of water including tides, current, storms, wind, rain, etc.), seismic and biological phenomena [2].

3) *Multipath Propagation*

The channel can be considered as a wave guide and due to the reflections at surface and bottom we have the consequence of multipath propagation of the signal. Multi-path propagation may be responsible for severe degradation of the acoustic communication signal, since it generates Inter-Symbol Interference (ISI). The multi-path geometry depends on the link configuration [3, 4]. Vertical channels are characterized by little time dispersion, whereas horizontal channels may have extremely long multi-path spreads. The extent of the spreading is a strong function of depth and the distance between transmitter and receiver.

4) *Attenuation*

Acoustic energy is partly transformed into heat and lost due to sound scattering by inhomogeneity. Attenuation which is mainly provoked by absorption due to conversion of acoustic energy into heat, which increases with distance and frequency. It is also caused by scattering a reverberation (on rough ocean surface and bottom), refraction, and dispersion (due to the displacement of the reflection point caused by wind on the surface). Water depth plays a key role in determining the attenuation [5].

5) *Doppler Shift*

Due to the movement of the water surface, the ray getting reflected from surface can be seen as a ray actually getting transmitted from a moving transmitter, and thereby, having Doppler shift in the received. When the receiver and transmitter are moving with respect to each other, the emitted signal will either be compressed or expanded at the receiver. Thereby, Doppler Effect is observed [6].

Table 1. Comparison of the Acoustic, Radio wave and Optical communication in underwater [7]

	Acoustic	Radio	Optical
Speed propagation	1500 m/s	3x10^8 m/s	3x10^8 m/s
Bandwidth	~KHz	~MHz	~10-150 MHz
Frequency band	~KHz	~MHz	~10^{14} - 10^{15} Hz
Transmission range	~50 m - 5 Km	~1 m – 100 m	~1 m – 100 m

2. OFDM

In wireless communications efficient and reliable transmission of information signals over challenging channels is a central issue. One way to achieve this is by using multi carrier modulation (MCM). The principle of MCM is to divide the transmission channel into a number of sub-channels or sub-carriers. Orthogonal frequency division multiplexing (OFDM) is a form of MCM where its carrier spacing is chosen so that each sub-carrier is orthogonal to the other sub-carriers. By orthogonal we mean that when the dot product of two deterministic signals is equal to zero, these signals are said to be orthogonal to each other. This will allow the sub-carriers spectra to overlap, and thereby increasing the spectral efficiency [8]. In OFDM the entire channel bandwidth is divided into several sub-bands as shown in figure 1. This gives a relatively flat frequency response over each individual sub-band. The systems throughput is the sum of the throughputs of all the sub-channels, this means that the data rate per sub-channel is only a fraction of the data rate of a conventional single carrier system having the same throughput. This property allows systems to achieve high data rates, while still maintaining symbol durations much longer than the memory of the channel. The result of this parallel modulation technique is that we avoid complex channel equalization and it reduces the susceptibility to various forms of impulse noise [9].

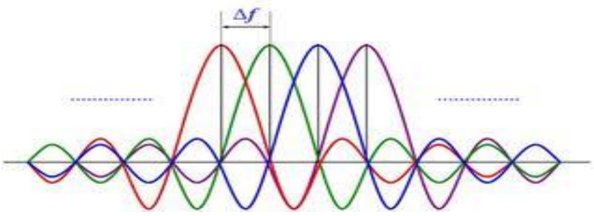

Figure 1: Spectrum of OFDM sub-carriers [10].

In practice, OFDM systems are implemented using a combination of fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT). The reason for this is that FFT are much more efficient to implement. The OFDM transmitter handles the source symbols (e. g. QPSK) in the frequency-domain. An IFFT block uses these symbols as input and transform the signal into the time-domain. The IFFT block takes N symbols, where N is the number of sub-carriers, and maps each symbol onto a sinusoidal basis function. Since the input symbols are complex, the value of the symbol determines both amplitude and phase of the sinusoid. The output of the IFFT block is an OFDM symbol which are the summation of the N sinusoids. The length of the OFDM symbol is NT, where T is the period of the input symbol. At the receiver the signal is transformed into frequency-domain again by an FFT block and the output is the symbols that where sent to the IFFT at the transmitter [8].

The presence of a multipath channel is a major problem for most wireless systems. In a multipath channel the signal reflects of several objects. At the receiver this results in multiple delayed versions of the transmitted signal, which causes the signal to be distorted. For an OFDM system this will cause two problems, intersymbol interference (ISI) and intrasymbol/intercarrier interference (ICI). Intersymbol interference occurs when the received OFDM symbol is distorted by the previous OFDM symbol. This problem can be solved by using a guard interval. By choosing an appropriate number of subcarriers in the system one can make the length of the OFDM symbol longer than the time span of the channel. This way the intersymbol interference will only affect the first samples of the received OFDM symbol. If we now use a guard interval in front of each of the OFDM symbols we can remove the effect of intersymbol interference. The guard interval could for example be a section of all zeros. The length of the guard interval should be chosen such that it is longer than the time span of the channel. At the receiver the guard interval is discarded since it contains no useful information, and this way the intersymbol interference is discarded as well [8]. In figure 2 it is illustrated how the use of guard interval removes intersymbol interference.

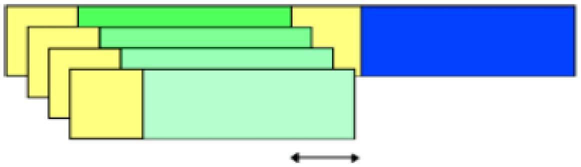

Figure 2: Intersymbol interference: The green symbol was transmitted first, followed by the blue symbol [8].

Intrasymbol/intercarrier interference is unique to multi carrier systems. This interference is due to interference between a given OFDM symbol's own subcarriers, which means that the OFDM symbol interferes with itself. The solution to this problems involves taking advantage of a discrete-time property. In discrete-time a convolution is only equivalent to a multiplication in the frequency domain if the signals are of infinite length or if at least one of the signals is periodic over the range of the convolution. By using a guard interval consisting of a given number of the last samples of the OFDM symbol, the OFDM symbol appears periodic when convolved with the channel and therefore the convolution is equivalent to a multiplication in the frequency domain. An important result of this is that the effect of the channel becomes multiplicative. This means that each sub-carrier's symbol will be multiplied by a complex number equal to the channel's frequency response at that sub-carrier's frequency. This multiplication will cause a complex gain (amplitude and phase) to each of the sub-carriers. In order to remove these effects a frequency domain equalizer is used. For a simple case with no noise this equalizer's response would be the inverse of the channel frequency response. A frequency domain equalizer is much simpler than a time domain equalizer. At the receiver the cyclic guard interval is discarded, and this way it also removes the effects of intersymbol interference [8].

The decision of the various OFDM parameters is a trade-off between various requirements. Often there are three main requirements to start with, bandwidth, bit rate and delay spread. By delay spread we mean the length of the channel impulse response. The guard time is dictated directly by the delay spread. The rule is that the guard time should be about two to four times the root-mean-squared of the delay spread, depending on the type of coding and QAM (quadrature amplitude modulation) modulation. Higher order QAM is more sensitive to ICI and ISI than QPSK, while heavier coding reduces the sensitivity to such interference. The symbol duration should be much larger than the guard time in order to minimize the signal-to-noise (SNR) loss caused by the guard time. A practical choice is to make the symbol duration at least five times the guard time, this implies a 1-dB SNR loss. The number of sub-carriers is found by the bandwidth divided by the sub-carrier spacing, which is the inverse of the symbol duration. This number can also be determined by the required bit rate divided by the bit rate per sub-carrier. The bit rate per sub-carrier is defined by the modulation type, coding rate and symbol rate [11, 12].

3. Numerical Analysis

The bit error ratio (BER) is a very important measure for communications systems. This is because it tells us something about how a certain signal to noise ratio (SNR) affects the received data. In figure 3 the calculated bit error ratio for the OFDM system is plotted against the SNR when only ambient noise is present on the channel. Here we see that the error is quite severe at SNR's up to about 12 dB. From 12 dB and up the error drops rapidly and from 18 dB the bit error is neglectable. This BER-curve tells us how much signal energy we need to use in order to achieve a certain probability for bit error. In this case a SNR above 16 dB should be sufficient.

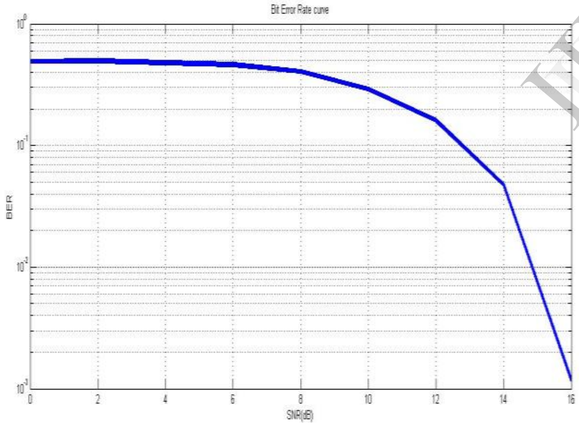

Figure 3: The BER as a function of SNR when adding ambient noise

When phase error is present on the channel together with ambient noise the probability for error increases. In figure 4 the bit error ratio for a channel with only noise present is compared to the bit error ratio when phase error also is present on the channel. Here we see that both the curves start out at a BER of approximately 0.5, but the difference becomes more clear when the SNR increase. In order to achieve a BER in the order of 10^{-3} the phase error increases the demand of the SNR with about 4 dB.

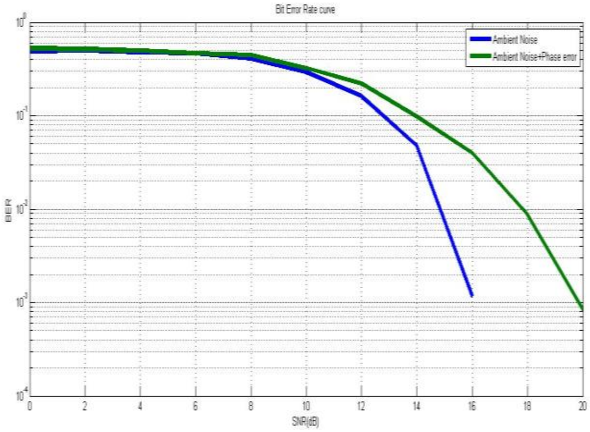

Figure 4: The BER as a function of SNR when adding phase error

Figure 5 shows the BER curves with and without multipath. Here we see that the two curves follow each other closely until the SNR reaches about 14 dB. After 14 dB the bit error ratio with multipath does not drop as quickly as the bit error ratio without multipath. At a BER of order 10^{-3} the difference in SNR is about 2 dB for the two curves.

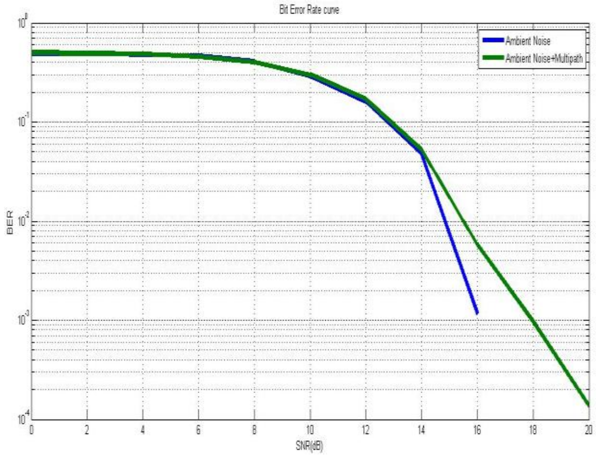

Figure 5: The BER as a function of SNR when adding multipath

In figure 6 four bit error ratio curves are plotted. The blue curve is the BER when only noise is present on the channel, the green is the BER when noise and phase error is present and the red curve is the BER when noise and multipath is present. The blue light curve is the bit error ratio for the channel when all of these are present. Here we see that the BER curve for this channel is approximately the sum of the blue, red and green curves. In order to achieve a bit error ratio in the order of 10^{-2} the signal to noise ratio must be 20 dB or more.

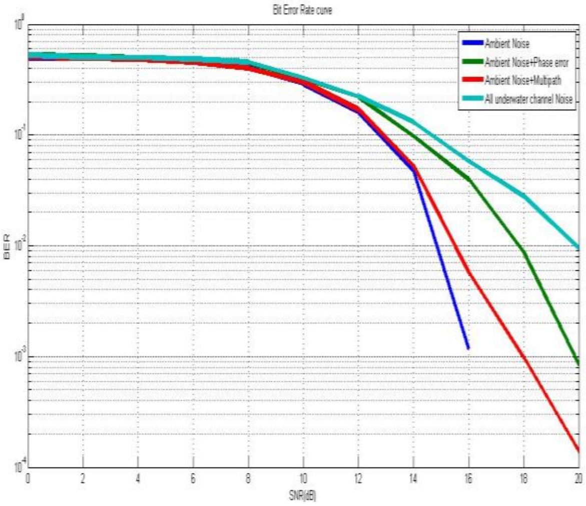

Figure 6: BER for UWA communication channel

4. Conclusion

The OFDM-system developed in this study has been thoroughly tested through simulations. It has been tested using several different communications channels containing noise, multipath, phase error or a combination of these. The results of these simulations shows that the OFDM-system handles these challenges quite well. When only noise is present on the channel the requirement of the signal to noise ratio (SNR) is 16 dB or higher (BER in the order 10^{-3} or less). When also adding a linear phase error with a maximum of 2π, we see that the requirement of the SNR increases by approximately 4 dB. But the most interesting part was to observe how the system handles multipath, since this should be the strength of the OFDM-system. The simulated channel impulse response consisted of five arrivals, where four were relatively strong reflections. The length of the impulse response was approximately 4 ms. In the results we see that when noise and multipath were present on the channel the requirement of the SNR was 18 dB, an increase of only 2 dB compared to a channel containing only noise.

5. References

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