Multi-Carrier Wideband Acoustic Communications

Orthogonal frequency division multiplexing (OFDM) offers a viable approach to high-rate, low-complexity wireless underwater communications

Introduction

High-rate, bandwidth-efficient underwater acoustic communications have traditionally used single-carrier modulation that relies on adaptive equalization to overcome the frequency-selective distortion of a multipath channel [1]. This method has served as a basis for real-time implementation of a high-speed acoustic modem at the Woods Hole Oceanographic Institution (the WHOI micro-modem), and it has been successfully demonstrated in a variety of underwater channels.

An alternative method for communicating over frequency-selective channels is multi-carrier modulation. In a multi-carrier system, the available bandwidth is divided into many narrow subbands, such that the channel distortion appears as flat (frequency-nonselective) within each subband. No equalization is thus needed per subband. Instead, modulation and demodulation have to be performed over multiple carriers.

Orthogonal frequency division multiplexing (OFDM) is a special case of multi-carrier modulation, in which rectangular pulse shaping is used, leading to an efficient modulator/demodulator implementation via the fast Fourier transform (FFT). For this reason, OFDM has found application in a number of radio systems, including the wire-line digital subscriber loops (DSL), wireless digital audio and video broadcast (DAB, DVB) , and wireless local area networks (IEEE 802.11 LAN). It is also considered for the fourth generation cellular systems.

While it offers an elegant solution to the multipath problem, OFDM requires extremely accurate synchronization. It can only tolerate a frequency offset that is much smaller than the carrier spacing Δf, as any residual offset will cause inter-carrier interference (ICI).

Methods for frequency synchronization in OFDM radio systems have been extensively studied, and numerous algorithms have been proposed [2]. The majority of these algorithms are based on the assumption that the system is narrowband, i.e. that its bandwidth is negligible compared to the center frequency, $B \ll f_c$. Such an assumption is rarely justified in an underwater acoustic system. Acoustic propagation is best supported at low frequencies, and a high-rate system is thus inherently wideband (even if its bandwidth is low in the absolute sense).

A frequency offset in an underwater acoustic system is caused by the transmitter/receiver motion. The Doppler effect is characterized by the ratio v/c of the relative transmitter/receiver velocity to the speed of sound: a transmitted frequency f_k appears at the receiver as $f_k + f_k \cdot v/c$. Because the speed of sound underwater (1500 meters/second) is much lower than that of the electro-magnetic waves in air ($3 \cdot 10^8$ meters/second), the resulting Doppler distortion is much more pronounced. An autonomous underwater vehicle may move at a speed of few meters/second, with the resulting Doppler rate a=v/c on the order of 10^{-3}. Even in the absence of intentional motion, freely suspended transmitters and receivers are subject to drifting at a speed that may be a fraction of a meter/second in calm conditions.

In a wideband system, motion-induced Doppler distortion results in frequency shifting that is not uniform across the signal bandwidth. When OFDM is used, the lowest and the highest carrier may experience markedly different Doppler shifts. In other words, since the bandwidth is not negligible with respect to the center frequency, the Doppler shift cannot be approximated as equal for all the subbands. Hence, many of the existing synchronization algorithms do not apply.

In comparison with terrestrial radio systems, OFDM has only been considered to a very limited extent for underwater acoustic systems. In this article, we report on the design and experimental demonstration of a low-complexity receiver algorithm that capitalizes on the ease of frequency-domain OFDM equalization, and has a capability to compensate for the non-uniform, time-varying Doppler distortion in a wideband acoustic system.

Receiver Algorithm

In an OFDM system, the input data stream, arriving at a rate of R bits/second, is converted into K parallel streams. The k^{th} data stream, $d_k(n)$, modulates a carrier of frequency $f_k=f_0+k\Delta f$, $k=0,\ldots K-1$. We consider a bandwidth-efficient modulation method such as phase shift keying (PSK) or quadrature amplitude modulation (QAM), and a uniform energy allocation across the subbands.

The K data symbols comprise one OFDM block, whose duration is $T=1/\Delta f$. A guard interval of length T_g corresponding to the multipath spread is appended to each block, so that adjacent blocks do not interfere at the receiver. The guard interval can be filled with a cyclic shift of the trailing signal samples, or with zeros. While cyclic prefix is a traditional choice that enables FFT demodulation without any pre-processing, zero-padding saves transmission energy.

Signal processing at the receiver involves three steps: initial synchronization, FFT demodulation, and post-FFT processing. Initial synchronization is performed using a dedicated high-resolution probe that precedes a frame of OFDM blocks. This probe is used to acquire the timing, and to make an initial estimate of the Doppler shifting. After removing the so-obtained frequency offset, and resampling the signal accordingly, FFT demodulation is performed. If there is no cyclic prefix, the signal of each OFDM block is overlap-added prior to FFT demodulation using the method of [3]. The guard interval is then discarded, and the useful signal is subject to FFT of the same size as that used at the transmitter. If the receiver is equipped with multiple hydrophones, one FFT is used for each received signal.

The receiver algorithm specifies post-FFT processing. The received signal in the k^{th} subband of the n^{th} OFDM block is modeled as

$\mathbf{y}_k(n)=\mathbf{c}_k(n)\, d_k(n) \exp\{j\theta_k(n)\} + \mathbf{z}_k(n)$

where $\mathbf{c}_k(n)$ is the channel gain, $\theta_k(n)$ is the phase distortion, and $\mathbf{z}_k(n)$ is the noise that includes any residual interference. The boldface letters denote column vectors that contain entries corresponding to the multiple receiving elements.

The signal model is crucial to the design of the receiver algorithm. Notably, since all the signal processing is performed digitally, there is no mismatch between the frequencies of local oscillators, and the phase distortion is modeled as a consequence of the Doppler effect:

$\theta_k(n)= \theta_k(n-1)+a(n)\cdot 2\pi f_k(T+T_g)$

The Doppler rate a(n) is assumed to be constant over one OFDM block, but may vary from one block to another. In this manner, the possibility of non-constant Doppler shift is accommodated, which is necessary when the speed and direction of transmitter/receiver motion may change with time.

The receiver performs minimum mean square error (MMSE) combining of signals received across an array, to obtain an estimate of the data symbol as

$d_{k,est}(n)= \mathbf{c}'_{k,est}(n)\, \mathbf{y}_k(n)\exp\{-j\theta_{k,est}(n)\}$

where the prime denotes conjugate transpose. In practice, the channel gains and the phases are not known, and moreover, they are time-varying. Hence, their adaptive estimates are needed to implement the receiver.

The channel gain varies much more slowly than the phase, and it can be estimated using a simple least squares algorithm. Phase estimation is based on the model of motion-induced Doppler distortion. This model is the key to the phase tracking algorithm, which estimates the Doppler rate a(n), and utilizes this *single* estimate to compute the phases for *all* the subbands. The details of the algorithm can be found in [4].

Experimental Results

One of the questions that arise in the design of an adaptive OFDM system is the selection of the number of subbands K. For a given bandwidth $B=K\Delta f$, the bandwidth efficiency, defined as the ratio R/B of the number of bits/second transmitted per Hz of occupied bandwidth, increases with K. However, the symbol duration $T=K/B$ increases as well, making it more difficult to track the channel on a block-by-block basis. Also, the carrier separation Δf narrows, making the signal more vulnerable to Doppler. Hence, there is a trade-off in the selection of the number of carriers. Ideally, one should choose the greatest K for which the receiver performance is still satisfactory.

To assess the system performance in various configurations, an experiment was conducted at the Woods Hole Oceanographic Institution in the fall of 2005. The transmitter and receiver were deployed from two vessels stationed in 12 meters of water at a distance of 2.5 kilometers. The receiver employed a 12-element, 1.5 meters long vertical array. The signal occupied the frequency range between 22 and 46 kHz. (With a bandwidth of 24 kHz, and a center frequency of 34 kHz, this is certainly not a narrowband system.) The experimental signals were generated for varying number of subbands, ranging from 128 to 2048 in doubling steps. Quadrature PSK modulation and zero-padding were used.

The received signal was directly A/D converted, and all processing was performed digitally. After conversion to baseband, the received signals were frame-synchronized by matched filtering to a high-resolution probe.

To illustrate the results of signal processing, let us consider an example of a K=1024 OFDM frame. The first data block contained known symbols which were used to initialize the algorithm. No training symbols were used thereafter. The receiver operated over 32 OFDM blocks of 1024 symbols each. The estimates of the data symbols $d_{k,est}(n)$ provided a clean scatter plot, and no decision errors. The overall bit rate in this case was about 30 kilobits/second, with a bandwidth efficiency of 1.26 bits/second/Hz. Excellent results are thus achieved at a minimal computational complexity.

The estimate of the Doppler rate a(n) was also recorded during signal processing. A significant time-variation in the Doppler rate was observed over the signal frame. However, the variation was slow from one block to another, which allowed the receiver to track it. The absolute level of the Doppler rate did not exceed 10^{-5}, and the assumption of negligible ICI is thus justified. The phases corresponding to the estimated Doppler rate reflected tracking of a wave-like motion. The corresponding relative velocity of 0.25 meters/second is consistent with the experimental conditions.

The channel estimates $\mathbf{c}_{k,est}(n)$, which represent the transfer functions corresponding to various receiving elements, showed that the channel exhibits a high degree of frequency selectivity, which varies with the receiver location. Time variation proved to be slow enough to enable successful tracking, but we note that adaptive channel estimation is crucial to the overall system performance.

The algorithm performance was quantified by the mean squared error (MSE) of the estimated data symbols. In time, the MSE was evaluated for each OFDM block by averaging over all subbands. In frequency, the MSE was evaluated for each subband by averaging over all received OFDM blocks. The system performance was observed to be uniform over time, while in frequency it was better for those subbands that contained more energy. The overall MSE was also evaluated as the average taken over both time and frequency.

Excellent results were obtained for all K below 1024. At K=2048, however, the performance degraded, confirming our conjecture about the existence of an optimal number of carriers to use in a given OFDM system.

Conclusion

Experimental results indicate that OFDM is a viable technique for high-rate underwater acoustic communications. This technique should be considered as a low-complexity alternative to traditional single-carrier modulation.

The major impediment to low-complexity, post-FFT processing of OFDM signals on an (ultra) wideband acoustic channel is the motion-induced Doppler distortion. The key to successful performance of the algorithm proposed is in the non-uniform Doppler tracking and the spatial signal combining. Its low computational complexity comes from the FFT-based equalization in the frequency domain, and phase tracking based on adaptive estimation of a single parameter (the Doppler rate) used to compute phase distortion for all the carriers.

Future work will focus on experimental testing in varying conditions, and notably in mobile scenarios. Methods that exploit correlation among the subbands of an OFDM signal, such as that investigated in [5], will be used to perform smoothing in the frequency domain in addition to temporal filtering. Further improvement in bandwidth efficiency should be sought through the use of multi-input multi-output (MIMO) OFDM configurations. Longer term research should address the possibility of optimal energy allocation across subbands, as well as algorithm design for channels that cannot be modeled by a single Doppler rate.