Letters

High-Data-Rate Ultrasonic Through-Metal Communication

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***Abstract*—A link-adaptive frequency division multiplexing (OFDM) ultrasonic physical layer is proposed for high-data-rate communications through metal walls. The ultrasonic link allows for communication without physical penetration of the metal barrier. Link-adaptive OFDM mitigates the severe frequency-selective fading of the ultrasonic channel and greatly improves throughput over impulse or narrowband communication systems. Throughput improvements of 300% are demonstrated over current narrowband low-frequency techniques, and show improved spectral efficiency over high-frequency techniques found in the literature.**

I. Introduction

Many applications of industrial control networks require transmission of signals in environments in which metallic structures impede connectivity [1]. Ultrasonic wireless links have been suggested as a means for mitigating this problem by passing data through the metal barrier without physically penetrating it, thereby preserving its structural integrity [2]. The ultrasonic links, however, are a bottleneck to network throughput because of the latency of sound wave propagation and the reverberant nature of acoustic channels that greatly limits the bandwidth of the communication link. Narrowband approaches have been limited by the frequency-selectivity of the channel and can only achieve maximum data throughput up to 5 Mb/s [3], [4]. An alternative high-frequency technique is proposed in [5] and [6]. [5] achieves a comparable data rate, but at spectral efficiency of 0.45 b/s/Hz, whereas the proposed technique improves the spectral efficiency to 3 b/s/Hz, and [6] operates at lower rate with different center frequency, subcarrier spacing, and modulation format. The solution proposed in this letter makes use of orthogonal frequency division multiplexing (OFDM) to divide the frequency-selective channel into orthogonal flat fading bands. Use of OFDM allows for a significant increase in throughput of the ultrasonic link without using highly complex equalizers to correct frequency-selective fading. Additionally, bit-loading algorithms can make use of the frequency-selective and relatively stable channel, allowing for both higher throughput and the ability to probabilistically constrain symbol estimation error. Using an experimental testbed, and making use of these communication techniques, we have demonstrated that raw throughput rates of up to 15 Mb/s are achievable through the ultrasonic channel.

Manuscript received February 29, 2012; accepted May 23, 2012. This study was supported in part by the National Science Foundation under grant numbers CNS-0923003 and CNS-0854946 and by the Office of Naval Research under project N05-T020: Wireless Sensing for Survivable Machinery Control.

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DOI http://dx.doi.org/10.1109/TUFFC.2012.2426

II. Ultrasonic Channel

The ultrasonic channel, pictured in Fig. 1, consists of two ultrasonic transducers separated by a metal barrier. The through-metal link in Fig. 1 was prototyped using two 6-MHz, 0.25-in (6.35-mm) contact transducers (A112s non-destructive testing contact transducer, Panametrics NDT, Waltham, MA) separated by a 0.25-in-thick (6.35-mm-thick) mild steel plate. Between each of the transducers and the metal plate is a layer of couplant gel (D-12 gel-type Couplant D, Panametrics NDT) designed to maximize the acoustic power transfer between the two components. The transmitting transducer is driven by a function generator; the receiving transducer is connected to an oscilloscope which captures the received signal. Both the generator and oscilloscope are connected to a PC which implements the transmitter and receiver in Matlab (The MathWorks Inc., Natick, MA). The resultant channel is band-limited with severe frequency selectivity, but has a high degree of stability because of the slowly varying nature of the acoustic channel [7].

III. Physical Layer Model

The physical layer uses a direct up/down conversion front-end to exploit in-phase and quadrature components of the carrier. This physical layer structure allows for multi-level quadrature amplitude modulation (QAM) to increase the data transmission rate by transmitting more bits per symbol.

A. Transmitter

The baseband signal is constructed with 512 orthogonal subcarriers; 496 carry data symbols, 6 are pilot tones used for correcting residual carrier frequency offset (CFO) from clock drift, and 10 are reserved carriers that provide a guard band to avoid interference from carrier energy. A cyclic prefix of 128 samples, or 25% of each OFDM word, is appended to each OFDM word to capture ISI from channel echoing. Each subcarrier can be loaded with anywhere from 1 to 14 bits, resulting in packet information rates in the range of 496 to 6944 uncoded bits per OFDM symbol. The OFDM symbols are sent at a rate

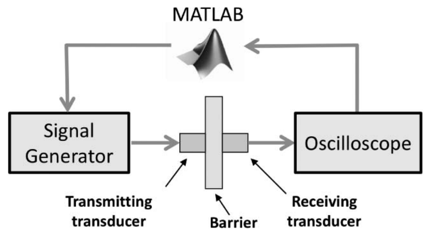

Fig. 1. Experimental model of ultrasonic channel.

of 7.81 ksymbols/s. The bandwidth of transmissions is 5 MHz at a center frequency of 8.3 MHz.

B. Receiver

The receiver estimates the complex channel gain independently on each subcarrier from two training symbols, and uses the sample mean as the unbiased estimator. The received OFDM symbols are then corrected by zero-forcing equalization from the measured channel estimates. Finally, pilot subcarriers are used to correct residual frequency offset resulting from clock drift over the duration of the packet.

IV. Experimental Results

Fig. 2 displays the magnitude of the channel gain estimates for each subcarrier. From the channel estimates, it is clear that the channel is highly frequency selective. The periodic nature of channel fading is due to the consistent echoing of signal energy in the metal wall. The frequency spacing of the fades is related to the round trip time of the signal energy, which can be determined by the physical thickness of the wall and the speed of sound in the metal.

As a baseline, QPSK transmissions are sent over the channel to estimate signal integrity, with a peak transmit power of 3 dBm. The post-processing signal-to-noise ratio (PP-SNR) is estimated as the ratio of the average symbol power to the average squared error vector magnitude (EVM). PP-SNR is used as a metric to estimate received signal quality. From measurements of 10 000 transmitted packets, the average PP-SNR is estimated to be 23.5 dB averaged over all symbols transmitted on all subcarriers. Assuming a circularly symmetric Gaussian distribution for the received symbol error and a flat fading channel, the estimated uncoded bit error rate (BER) can be approximated to be on the order of 10^{-28}; the estimate is obtained from Bayesian analysis of hard decision decoding and tail function analysis of the statistically modeled EVM. This high degree of signal integrity can be attributed to the high efficiency coupling of signal energy from

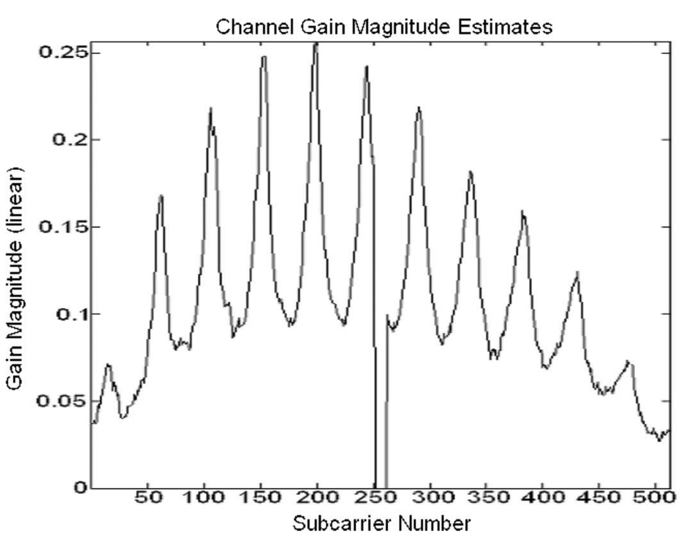

Fig. 2. Channel gain magnitude estimate from channel training.

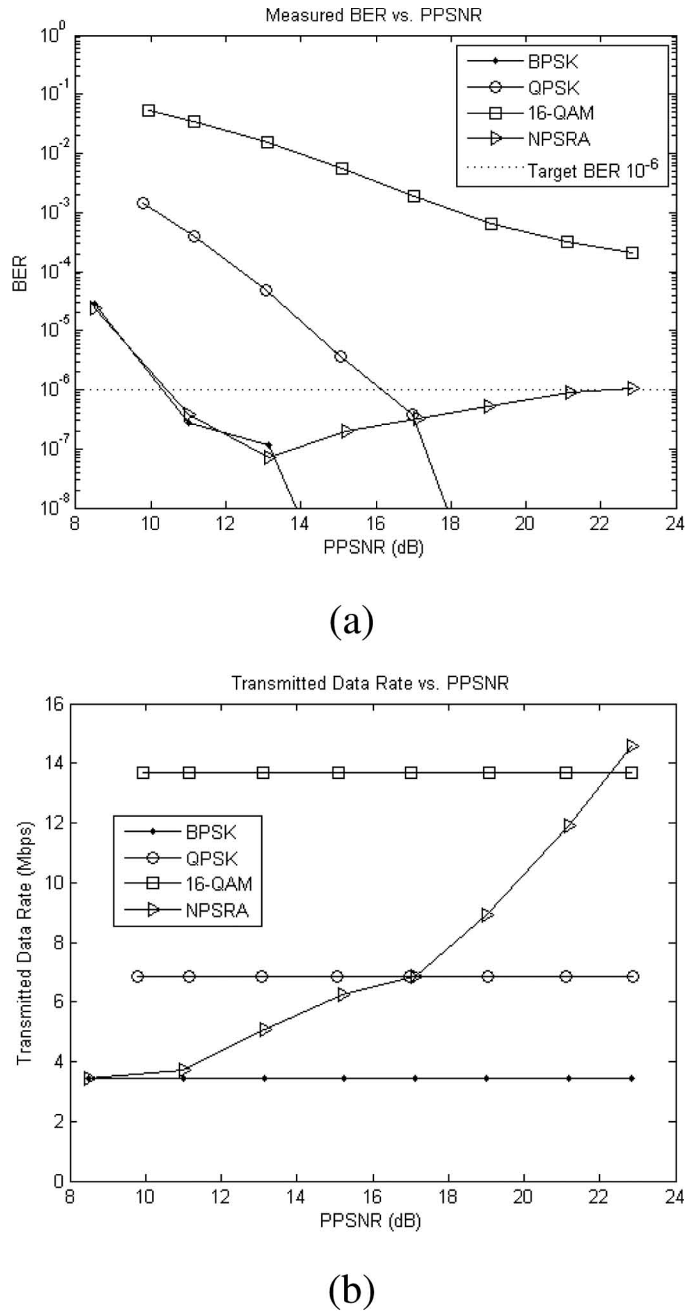

Fig. 3. (a) Bit error rate (BER) and (b) throughput versus average post-processing signal-to-noise ratio (PP-SNR) for the ultrasonic link.

the transmitter to the receiver and low levels of co-channel interference and thermal noise present in the link. These factors result in high-fidelity channel estimates and limited noise enhancement from equalization. The throughput for the QPSK physical layer is 7.2 Mb/s, constituting a 44% improvement in throughput over the state of the art in narrowband ultrasonic links, while maintaining a high degree of signal integrity [3], [4].

V. Link-Adaptive Modulation

The channel estimates shown in Fig. 2 indicate that using a single constellation order across all subcarriers may be spectrally inefficient, given the high variability of channel gain. Adaptive bit loading has been previously considered in conventional radio-frequency OFDM wireless systems to improve the spectral inefficiency in such channels [8]. In practice, these algorithms have shown limited improvement because of the non-stationary nature of conventional wireless radio networks and the added overhead of using feedback to maintain accurate estimates of channel information. However, the ultrasonic channel lends itself to this approach because the periodic echoes of the channel result in a high degree of frequency selectivity, whereas the slowly varying nature of the channel ensures that channel estimate information will remain accurate for the transmission of many packets.

The non-power-scaled rate-adaptive (NPSRA) bit-loading algorithm presented in this paper is a fixed-power modification of the algorithm provided in [8]. The bit-loading approach first performs training to estimate the channel gains and expected error vector magnitude of transmitted symbols on a subcarrier basis. Given these estimates, a lookup table is used to estimate the highest achievable modulation order on each subcarrier (ranging from BPSK to 2^{14}-QAM) that meets an *a priori* symbol error constraint of 10^{-6}. Figs. 3(a) and 3(b) show the expected bit error rate and throughput achievable with the NPSRA scheme as a function of PP-SNR. As a reference, both figures also include the measured performance for fixed-rate schemes in which the same modulation order (results shown in Fig. 3 ranging from BPSK to 16-QAM) is used on all subcarriers. PP-SNR is varied by adding white Gaussian noise of power from -3 dBm to -13 dBm. Figs. 3(a) and 3(b) show that at the lowest values of PP-SNR, the NPSRA scheme has throughput and BER equal to BPSK. The results are comparable because the NPSRA scheme has allocated the minimum possible data rate and is still not meeting the target BER constraint. As PP-SNR improves, the NPSRA algorithm achieves better throughput by loading more data on higher quality subcarriers, and constrains BER by keeping data rates low on low-quality subcarriers. Furthermore, Figs. 3(a) and 3(b) illustrate the objective of throughput maximization, because the fixed-rate algorithms offer better BER performance below the constraint level but do not offer better throughput at those same levels of signal integrity. These results show that data rates on the order of 15 Mb/s are achievable in the given ultrasonic channel.

VI. Conclusion

Using OFDM communications can greatly improve reliable data throughput in metal channels by mitigating the highly frequency selective nature of the channel. Using fixed rates, OFDM communications can offer up to a 44% improvement in data rate over conventional narrowband communications techniques. Rate adaptive techniques can further enhance spectral efficiency to allow for throughput improvements of up to 300% in comparison to current ultrasonic technology. The unchanging nature of the acoustic channel allows for accurate estimation of the channel to be maintained with minimum overhead cost. These channel characteristics and improved channel estimation performance allow for significant improvement in throughput, making ultrasonic wireless links a viable technology for high-data-rate applications.

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