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Application of Adaptive OFDM Bit Loading for High Data Rate Through-Metal Communication

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***Abstract*—The acoustic through-metal channel is characterized by strong multipath components caused by the echoing of acoustic energy within the channel. Transmission at high data rates is therefore difficult to achieve with traditional single-carrier systems. This paper applies an adaptive bit-loading technique to the transmission of digital signals through metal barriers using ultrasonic signaling. The multi-carrier approach discussed here allows us to mitigate severe frequency selectivity of the through-metal communication link and improve spectral efficiency by exploiting the stationary nature of the channel. Experimental performance of bit loading is examined in an ultrasonic through-metal channel. Our results indicate that non-power-scaled rate adaptive bit loading significantly outperforms non-adaptive modulation. Adaptive bit loading was shown to adhere to a strict BER constraint while increasing data rates by roughly 240% from values of 5 Mbps to approximately 12 Mbps when compared to narrowband modulation techniques.**

***Index Terms*—OFDM, Bit Loading, Rate Adaptation**

I. Introduction

Through-metal ultrasonic communication systems have been receiving growing attention from the U.S. Navy, which has shown interest in deploying wireless sensing and control networks onboard their ships [1]–[3]. To address wireless network reliability issues throughout the vessel, hybrid RF/ultrasound networks have been proposed to interconnect isolated RF wireless networks and achieve more reliable coverage. However, due to the unique acoustic qualities of the ultrasonic channel, the effects of echoing result in large delay spread and a highly frequency selective, slow fading channel that severely limits the channel's coherence bandwidth when using conventional narrowband modulation schemes. Orthogonal frequency-division multiplexing (OFDM) is thus an ideal candidate for data transmission in these environments.

OFDM mitigates frequency selectivity without increasing equalization complexity at the receiver. By dividing the wideband transmission channel into several orthogonal narrowband channels, each sub-frequency can be treated as a single flat fading channel. This division allows for various forms of adaptive modulation techniques, such as Adaptive Bit Loading (ABL), to be performed on each subcarrier to increase spectral efficiency. While ABL for OFDM has been extensively considered for RF systems [4]–[8], these systems face significant challenges related to training feedback overhead and channel estimation inaccuracies. While the ultrasonic through-metal communication channel is highly frequency selective, its slow varying nature makes OFDM and ABL techniques particularly effective. The contribution of this paper is to introduce ABL for OFDM-based ultrasound systems and quantify the benefits of these techniques.

This paper presents the measured results of OFDM ABL in ultrasonic through-metal channels. We compare adaptive and non-adaptive OFDM systems. Section II will introduce and discuss the ultrasonic channel model used for experimentation, Section III will present the OFDM system model, physical layer, and bit loading implementation. Section V describes the experimental setup for the results presented in Section VI and Section VII will conclude the paper.

II. Ultrasonic Through-Metal Channel

A number of industrial control network applications require transmission of signals in environments where metallic structures impede connectivity [9]. One example includes the augmentation of isolated RF networks on navy vessels, where the use of cables or wires that penetrate the metallic walls is undesirable due to the fact that the vessel must remain watertight. Ultrasonic wireless links have been suggested to mitigate this problem by transmitting data through the metallic barrier without mechanical penetration [10]. Nonetheless, the sound wave propagation latency and the reverberant nature of the acoustic channel greatly limit the ultrasonic communication link bandwidth, making ultrasonic links a bottleneck to network throughput.

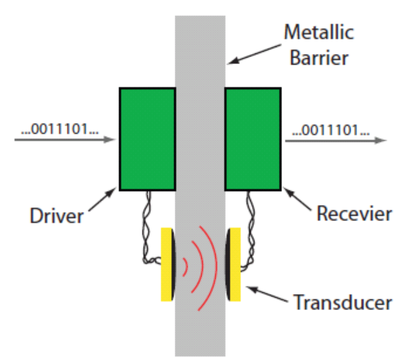

Fig. 1. Through-Metal Data Transceiver

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In the through-metal data transceiver shown in Fig. 1, data enters the left-hand side transceiver labeled 'Driver' and is transmitted in the form of ultrasonic energy through the metal bulkhead. Data is received by the transceiver on the right and recovered without mechanical penetration of the barrier. The total ultrasonic channel can therefore be considered the interconnection of the ultrasonic transducers and the metal barrier separating them, as modeled by the relationship of the components shown in Fig. 2.

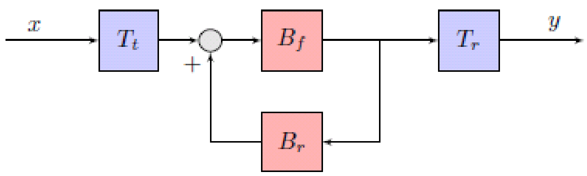

Fig. 2. Decomposition of the Ultrasonic Channel

Transducers on the transmitting and receiving sides of the barrier, T_t and T_r, respectively, perform the conversion between electrical and acoustic energy. The bulkhead is represented as an interconnection of two paths - the forward path, B_f, and the reverse path, B_r. Mismatches in acoustic impedance between the transducers and the barrier cause reflections within the barrier that are modeled by the feedback connection in Fig. 2. Experimentation has shown that the assumption of linearity for the ultrasonic channel appears valid under the operating conditions such as amplitude and frequency ranges of the ultrasonic channel [1]. Under this assumption of linearity, the transfer function of the block diagram in Fig. 2 can be described as

$$H_c = \frac{T_t B_f T_r}{1 - B_r B_f} = \frac{P}{1 - E} \qquad (1)$$

$$P = T_t B_f T_r, \quad E = B_r B_f$$

We denote the components P and E as the *primary* and *echo* paths of the channel, respectively. While the primary path response is dominated by the resonant characteristics of the transducer, the echo path characteristics are dominated by the acoustic impedance mismatch at the transducer-barrier junctions. The presence of this echo path leads to severe inter-symbol-interference (ISI) in the channel.

A measured frequency sweep of the ultrasonic channel of Fig. 1 is depicted in Fig. 3. The deep nulls in the response are directly related to the acoustic echoing in the channel, where null-to-null spacing is a function of the reciprocal of the channel round trip echo period. The frequency selectivity caused by the strong echoing observed in the acoustic channel makes high-speed communication a challenge. In the next section, we describe the OFDM-based transceiver designed to counteract the echo-induced channel interference.

III. Adaptive OFDM Technique

An OFDM system with a total of N carriers is considered. A block diagram of the system including adaptive processing is

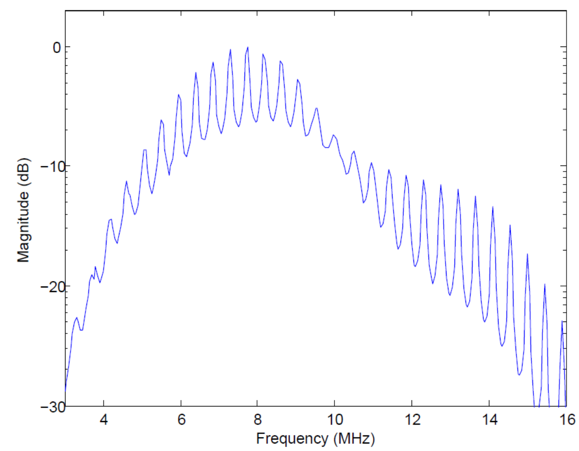

Fig. 3. Through-Metal Channel Magnitude Response

shown in Fig. 4. Note that ABL requires channel feedback and assumes that the channel remains stationary over a minimum duration of two packets. Thus, at least one non-adaptive transmission must first be performed to acquire channel state information. In the implemented ABL algorithm, a single, size N vector consisting of error vector magnitudes (EVM) is estimated for each subcarrier at the receiver. Assuming this information is available at the transmitter, the ABL algorithm calculates a suboptimal bit distribution provided a priori constraints on desired performance parameters including bit error rate (BER) and total available transmit power.

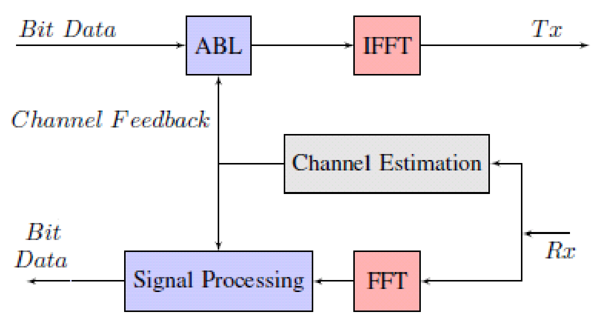

Fig. 4. Adaptive Bit Loaded OFDM System [4]

The source bits are modulated at the transmitter in accordance with the bit distribution determined by ABL algorithm. The information is converted to the time domain using an IFFT and transmitted over the ultrasonic channel. At the receiver, the data is reverted to the frequency domain via a FFT, equalized, demodulated, and decoded.

For each of the N subcarriers, the system can be mathematically modeled as a linear equation given by

$$y_k = \sqrt{e_k} h_k x_k + n_k \qquad 1 \leq k \leq N \qquad (2)$$

where e_k is the power associated with the k^{th} subcarrier, h_k and x_k are the k^{th} subcarrier channel response and transmitted symbol vector, respectively, and n_k is the additive white Gaussian noise (AWGN) of the k^{th} subcarrier. The resulting system for all loaded subcarriers can also be expressed as a vector channel matrix of length N.

The channel for the k^{th} subcarrier can be estimated using (2) and known training data as shown by (3). In the equation below, h_{Tr_k} is the training channel, x_{Tr_k} is the k^{th} known training symbol, and n_{Tr_k} is the k^{th} subcarrier AWGN noise factor.

$$\hat{h_k} = \frac{y_k}{x_k} = h_{Tr_k} + \frac{n_{Tr_k}}{\sqrt{e_k} x_{Tr_k}} \qquad 1 \leq k \leq N \qquad (3)$$

The channel estimated by (3) is used to equalize the received data symbols through zero forcing as in (4).

$$\hat{x_k} = \frac{y_k}{\hat{h_k}} = \frac{\sqrt{e_k} h_k x_k}{\hat{h_k}} + \frac{n_{Tr_k}}{\hat{h_k}} \qquad 1 \leq k \leq N \qquad (4)$$

In this implementation, ABL for individual subcarriers is determined by the EVM, as calculated using (5) using the same notation as (2). Initial channel estimation error and the presence of noises during symbol estimation affect the calculation of EVM, as shown by (4).

$$EVM_k = \overline{|\hat{x_k} - x_k|^2} \qquad (5)$$

IV. Bit Loading Implementation

Previous ABL algorithms developed by Chow, Cioffi, and Bingham in [11] include a rate adaptive bit loading procedure that strives to maximize the number of bits per OFDM symbol under a fixed energy and BER constraint. This is shown in (6) and (7) where N is the number of subcarriers, ε_k and g_k denote the k^{th} subcarrier symbol energy and gain, respectively, Γ is the SNR gap - a quantity used to measure the proximity of discrete signal constellations to their theoretically achievable channel capacity - and $\bar{\varepsilon_x}$ is the average energy per dimension for the signal constellation x [11], [12].

$$\max_{\varepsilon_k} b = \sum_{k=1}^{N} \frac{1}{2} \log_2 \left(1 + \frac{\varepsilon_k g_k}{\Gamma}\right) \qquad (6)$$

$$s.t. : N\bar{\varepsilon_x} = \sum_{k=1}^{N} \varepsilon_k \qquad (7)$$

As seen in (6), the adaptive algorithms in [11] utilize the SNR gap concept. The SNR gap is dependent on a target probability of symbol error assuming equiprobable messages and therefore relates the receiver SNR to a target symbol error rate [13]. Similarly, the ABL implementation in this paper exploits the relationship between SNR and error probability through the use of channel Post-Processing SNR (PPSNR) (8). Though not a one-to-one ratio, the PPSNR is used as a metric for adaptation rather than the SNR due to practical issues. Therefore, bit loading decisions performed by the adaptive implementation rely on the statistical evaluation of the received symbol distribution as characterized by the EVM and utilize the probability of bit error for M-ary gray-coded, rectangular QAM modulation.

Equations for the SNR as a function of a given probability of error and modulation order M, for $M = 2^i$, $i = \{2, 4, 6, 8, 10, 12, 14\}$ were first formulated. From these equations, a look-up table of SNR values required to achieve BERs in the range of 10^{-4} to 10^{-6} for the seven modulation rates was generated offline. The EVM of the training transmission is the metric used to estimate the subcarrier channel PPSNR in (8). The suboptimal distribution of bits among the subcarriers is allocated by the algorithm based on a comparison of the calculated PPSNR and values in the offline look-up table. If the PPSNR for the k^{th} subcarrier is less than that required for QPSK, BPSK is selected as the default. Note that using the EVM of the training transmission was considered for estimating the bit distribution under the assumptions that the ultrasonic channel has limited additive noise and is stationary. Both assumptions have been experimentally validated.

$$PPSNR_k = \frac{1}{\overline{EVM_k}} \qquad 1 \leq k \leq N \qquad (8)$$

Lastly, existing bit loading algorithms created by Campello [14] aim to compute *e-tight* bit distributions, meaning that no other bit distribution can be calculated across all subcarriers such that an equivalent number of bits is loaded with less average energy within the individual symbols. However, the non-power-scaled rate adaptive implementation here does not "tighten" individual subcarrier symbol energy. Instead, it assumes average unit power. Although suboptimal and simplistic, this implementation has shown potential to reduce decoding errors over long time intervals when training is not performed in the ultrasonic channel. This error reduction results from the fact that scaling power according to older channel state information tends to have a greater negative effect on BER than suboptimal or inaccurate bit distributions.

The general ABL implementation presented in this paper performs non-power-scaled rate-adaptation on a subcarrier basis for modulation orders that are strictly even powers of two as described below.

1) Compute the $PPSNR_k$ for each of the N subcarriers with average unit power based on (8).
2) Let b_k be the number of bits loaded in subcarrier k and initialize to 0. Let SNR^{M-QAM} denote the SNR required to achieve M-QAM modulation while meeting the desired BER constraint.
3) For each subcarrier, determine the largest M such that:

$$PPSNR_k \geq SNR^{M-QAM} \qquad (9)$$

and set

$$b_k = \log_2(M) \qquad (10)$$

V. Experimental Setup

Baseband signal processing is first performed in MATLAB and loaded into an Agilent N5182A MXG vector signal generator, which synthesizes and up-converts the baseband

I/Q signals for communication over an ultrasonic channel. Panametrics A112-SRM transducers with 5 MHz bandwidth and 0.25-inch nominal element size are used. A 0.5-inch-thick piece of mild steel simulates a naval bulkhead through which ultrasonic energy is transmitted. The ultrasonic signals are captured at passband with an Agilent 54833A Infiniium oscilloscope and down-converted to baseband in MATLAB software, where final signal processing is also performed.

VI. Measured Results

Three fixed QAM modulation rates and the non-power-scaled rate adaptive (NPSRA) algorithm were applied in an ultrasonic channel for comparison. To simplify the system and the evaluation of the adaptive technique, the transmitted binary data was neither encoded nor interleaved. Of the 512 total parallel frequency subchannels available in the effective 5 MHz bandwidth, 496 carriers were used for the transmission of OFDM symbols, 6 were assigned as pilot signals, and 10 carriers were reserved to avoid interference from the 8.3 MHz carrier. Fixed-rate BPSK, QPSK, and 16-QAM packets were transmitted in succession to estimate the EVM for each subcarrier. The NPSRA bit loading algorithm then allocated a suboptimal bit distribution based on the mean subcarrier-based EVM of the fixed-rate packets. A total of 6000 packets containing 30 OFDM symbols were transmitted for each modulation order. The average BER and average received data rate were measured and analyzed over an average channel PPSNR range of roughly 8 dB to 22 dB. Packets containing any bits in error were considered as unsuccessful in transmission and therefore had no contribution to throughput.

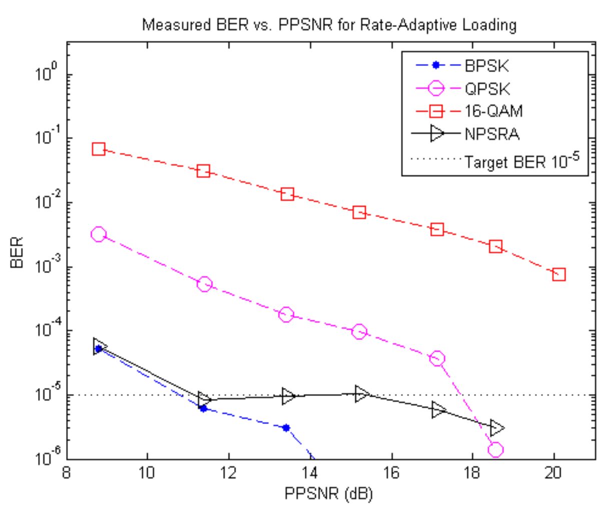

Fig. 5. Adaptive Loading Mean BER vs. Mean PPSNR

The measured results presented in Fig. 5 clearly indicate that the ABL implementation is capable of achieving and adhering to the strict 10^{-5} target BER for average PPSNR values in the range of roughly 11 dB to 18 dB, while fixed-rate QPSK and 16-QAM modulation do not. It is also shown in Fig. 6 that

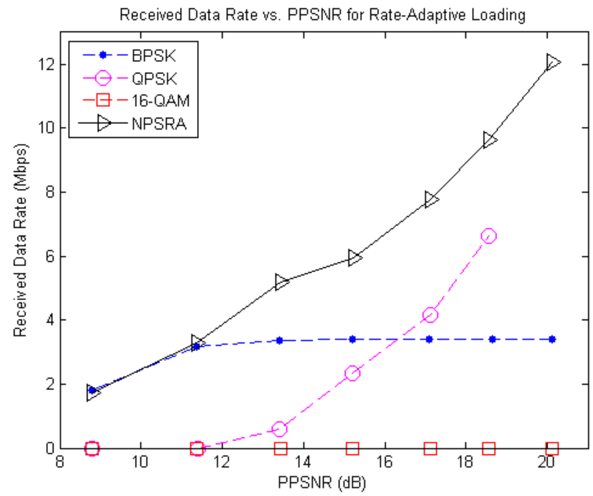

Fig. 6. Adaptive Loading Mean Received Data Rate vs. Mean PPSNR

ABL achieves larger average received data rates than fixed-rate QAM modulation when packets in error are considered to contain no successfully received information. This is due to the ability of ABL to increase spectral efficiency by taking advantage of higher-quality subcarriers while loading fewer bits on subchannels that cannot support high data rates for the given reliability constraint. The histogram in Fig. 7 depicts this optimization of data rates among the individual subcarriers based on measured channel conditions as described by the EVM. The figure provides measured results of the average number of subcarriers utilizing specific modulation rates with respect to the average PPSNR.

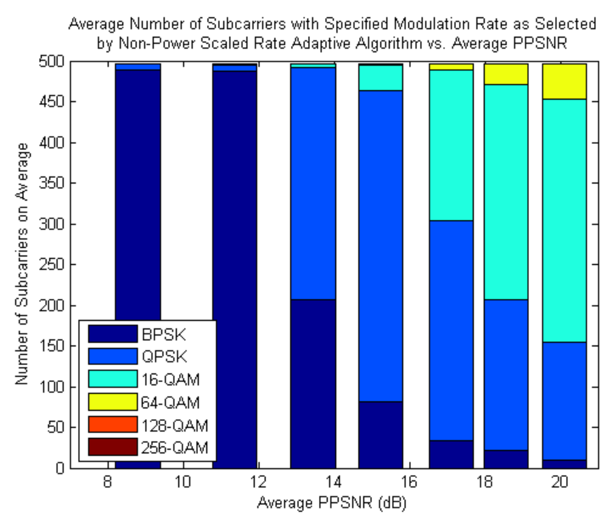

Fig. 7. Histogram of Adaptive Bit Allocation vs. Mean PPSNR

Despite that fixed-rate 16-QAM still experiences large error rates at higher average PPSNR values, Fig. 7 shows that the NPSRA algorithm is capable of utilizing 64-QAM on a number of carriers while still maintaining the desired BER.

As an example, at an average measured PPSNR of 18.5 dB, 25 subcarriers support 64-QAM, 264 support 16-QAM, and the remaining subcarriers only support QPSK or BPSK modulation provided that a BER constraint of 10^{-5} is desired. Thus, the high degree of frequency selectivity in the ultrasonic channel that results in ISI and increased BER for higher modulation orders can now be mitigated by using hybrid modulations capable of achieving transmitted data rates in between fixed transmission rates while still maintaining a desired level of reliability.

In comparison to narrowband modulation techniques previously found in literature [1], [15], Fig. 6 indicates that the use of OFDM and QAM modulation can increase data rates to slightly larger than 6 Mbps at an average PPSNR value of only 18.5 dB. At this same average PPSNR, ABL further increases the data rate to approximately 10 Mbps, constituting a 200% increase in received throughput when compared to the 5 Mbps obtained using narrowband modulation. For slightly larger average PPSNR values of 20 dB, a 240% throughput increase with respect to narrowband techniques is achievable. Finally, although not presented in this paper, average transmitted data rates of 15 Mbps for average PPSNR values in the range of 22 - 24 dB have also been demonstrated using the experimental testbed and OFDM-based adaptive techniques.

Clearly, the use of ABL in the ultrasonic channel is advantageous over fixed-rate modulation when both reliability and high data rates are desired. This advantage is particularly noticeable when examining Fig. 6. Note that all 16-QAM packets transmitted were considered to have received data rates of zero due to the fact that the packets contained bits in error. In fact, the average BER using 16-QAM modulation was larger than 10^{-3} for all measured average PPSNR values. Overall, Fig. 5 and Fig. 6 collectively suggest that without adaptation, adhering to a desired level of reliability while increasing throughput is not possible.

Finally, it should be mentioned that, although the presented adaptive techniques are capable of obtaining notable performance in the ultrasonic link, they still suffer from inaccuracies associated with channel estimation error, as shown in (4). Despite the fact that the ultrasonic channel is assumed to be stationary over the duration of multiple packets, the EVM values used for adaptation are based on the average of three preliminary fixed-rate transmissions. Therefore, suboptimal bit distributions are determined using channel information that is subject to change. Periodic and regular use of training packets can alleviate stale channel state issues.

VII. Conclusion

This work presents a variation of existing rate-adaptive bit loading algorithms for application in a slow fading, highly frequency selective OFDM through-metal communication system with a goal to improve spectral efficiency by exploiting the otherwise undesirable frequency selective nature of the channel. The measured performance of the ABL implementation was examined with final results indicating that non-power-scaled rate adaptive bit loading provides much higher data rates in comparison to non-adaptive modulation techniques despite its simplicity and sub-optimality in comparison to its power-scaled counterpart. For average PPSNR values of roughly 20 dB, the use of subcarrier-based rate adaptation in the ultrasonic channel is shown to increase throughput rates by roughly 240% in comparison to conventional narrowband modulation techniques while adhering to the strict desired BER constraint of 10^{-5}.

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