Efficient use of bandwidth for underwater acoustic communication (L)

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In a recent shallow water experiment, acoustic communication transmissions were carried out over the 10 to 32 kHz band in ~100 m deep water over a 3 km range. A natural question is how best to utilize that bandwidth. In one multiband approach discussed previously, the band was divided into four smaller subbands that were processed independently using time reversal decision-feedback equalizers (TR-DFEs). This letter presents a complementary wideband approach using data from the same experiment achieving a data rate of up to 60 kbits/s with 32 quadrature amplitude modulation. These results suggest that a wideband approach can be beneficial in terms of spectral efficiency with modest computational complexity using a TR-DFE.

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I. INTRODUCTION

Underwater acoustic (UWA) channels are characterized by large multipath spreads resulting in intersymbol interference (ISI) that degrades the quality of the received signal and requires compensation (i.e., channel equalization). The time varying nature of the multipath also requires continuous tracking of receiver parameters necessary for demodulation. An additional factor is that the available bandwidth in UWA channels is limited due to severe frequency-dependent attenuation of the physical medium. Consequently, high spectral efficiency (an information rate per hertz) is critical for achieving significant data rates, suggesting a phase-coherent system design along with high-order constellations.

A straightforward approach to achieving higher data rates is to increase the signal bandwidth (or transmission/signaling rate). For a given multipath channel, however, an increase in signaling rate leads to larger ISI spans (measured in symbols), thus requiring longer channel equalizers. The extent of ocean multipath (ISI) potentially can limit system performance through large noise enhancement (i.e., self-generated noise) and increased sensitivity to numerical errors, along with increased receiver complexity. Consequently, UWA communication systems frequently use modest bandwidths (e.g., a few kilohertz), resulting in low transmission rates.

Interestingly, there are two seemingly counterintuitive reports in the literature based on experimental results where an increase in transmission rate yielded better system performance. Stojanovic et al. suggested that a relatively simple explanation for the observation was attributed to the time-variability of the channel. That is, a smaller symbol duration with a high signaling rate enables better channel/phase tracking since the channel remains coherent over a large number of symbols at the price of increased complexity. However, lack of details about the source power allocation, transmitted symbol energy, and noise spectral density over the bandwidth (10 to 20 kHz) makes it difficult to draw definitive conclusions. For instance, if the noise spectral density were not flat over the bandwidth, it would have affected the received signal-to-noise ratio (SNR) for different signaling rates.

Separately, the tradeoff between symbol rate (R) and performance has been investigated recently in shallow water (11 to 19 kHz) using various data sets in terms of channels, constellations, and bandwidths. Due to the fact that the transmit power of the projector (PT) remained the same, the transmit symbol energy (Es = PT/R) decreased proportionally with an increase in symbol rate (R). As a result, the performance in terms of output SNR degraded as the symbol rate (or transmission bandwidth) increased. On the other hand, constraining the transmitted symbol energy (Es) to be the same, a modified experimental result summarized in Fig. 3 of Ref. 5 indicates that indeed the performance can improve with an increase in symbol rate. It should be mentioned, however, that the environment was relatively time-invariant over the transmission period of the communication data packets (3-s), as opposed to the time-varying channel in Ref. 4 considered responsible for the performance behavior. Further taking into account the relatively flat noise spectral density (N0) over the frequency band of interest (11 to 19 kHz), the constraint on input symbol energy can be extended to the input SNR defined by Es/N0.

These two data-related examples suggest that a natural question is how best to utilize a large bandwidth when it is available for UWA communication—as multiple bands (multi-carriers) or as a single wide band (single-carrier). While UWA research activities have focused mainly on single-carrier communication with various bandwidths, there are two notable exceptions. In order to mitigate large ISI spans in a ~100 m shallow water region off the west coast of Kauai, HI (MakaiEx), Roy et al. explored multiband transmissions where the available bandwidth (27 to 50 kHz) was divided into several subbands with guard bands in between. Most recently, Song and Badiey presented multiband communication results exploiting a large available bandwidth (10 to 32 kHz) at 3-km range during the KAM11 experiment.
In the same experiment, wideband single-carrier communication signals also were transmitted, providing a rare opportunity to compare these two different approaches under similar environmental conditions using the same hardware (both source and receiver). Although each approach is not optimized for its best performance, the comparison will provide valuable insight into the use of the available bandwidth in UWA channels.

Section II reviews channel equalization in UWA channels along with motivation behind multiband communication. Section III describes the KAM11 experiment and relevant parameters. Section IV presents single-carrier communication results which are compared to the multi-carrier communication results reported in Ref. 7, followed by a discussion.

II. CHANNEL EQUALIZATION

There are two common approaches to channel equalization in UWA communication: (1) Multichannel decision-feedback equalizer (M-DFE) (Ref. 4) and (2) time reversal (TR) combining followed by a single channel DFE (TR-DFE). In theory, both approaches provide a similar performance in terms of output SNR. Depending on environments (or channels), however, one approach can be beneficial over the other in terms of computational complexity and/or robustness. For instance, if a channel has many multipaths with a large delay spread, the TR-DFE which can handle significant ISI with modest complexity outperforms the M-DFE. On the other hand, the TR-DFE which is based on knowledge of the channel requires frequent channel updates to accommodate time-varying channels (i.e., block-based implementation). The two approaches are described and compared in Ref. 8 using experimental data collected in a shallow water environment.

The use of multiband (multi-carrier) transmissions in Ref. 6 was motivated as a practical compromise between receiver complexity and carrier phase tracking capability where the available bandwidth (27 to 50 kHz) was divided into several subbands with guard bands in between (see Fig. 2), referred to as frequency-division multiplexing. Although multiband communication requires a shorter equalizer for each subband, it may be inefficient in using the bandwidth or spectrum because usually it requires extra space or guard bands to keep the parallel modulated carriers from interfering with one another. The objective of this paper is to compare single wideband and multiband transmissions using experimental data.

III. KAM11 EXPERIMENT

The Kauai Acomms MURI 2011 (KAM11) was a multi-university research initiative (MURI) experiment focused on studying the coupling of oceanography, acoustics, and underwater communication in a dynamic shallow water environment. Similar to the MakaiEx experiment, the KAM11 experiment was conducted off the west coast of Kauai, HI, in a roughly 100-m downward refracting environment, from June 23 to July 12, 2011. Since the multi-carrier transmissions reported in Ref. 7 were collected at 06:16 UTC on JD183 (July 3, 2011), this letter will analyze single-carrier communication signals transmitted around that period to ensure similar channel conditions for comparison purposes.

A vertical receive array (VRA) was deployed in ~106 m of water at 3 km range from an 8-element source array suspended from the R/V Kilo Moana in dynamic positioning mode as shown in Fig. 1(a). The middle element (Ch. No. 4) at 61.6 m was chosen as the source for both single- and multi-carrier communications exploiting a large bandwidth available (10 to 32 kHz). The source level was 185 dB re 1 \mu Pa at 1 m. The VRA consisted of 16 elements spanning a 56.25 m aperture with 3.75 m element spacing, covering the middle and lower portion of the water column. The channel impulse response (CIR) estimated from a 100-ms linear frequency modulation (LFM) probe signal is displayed in Fig. 1(b) indicating about $T_d = 10$ ms delay spread of the channel.

The multiband communication signals reported in Ref. 7 divided the entire frequency band (10 to 32 kHz) into four subbands with guard bands in between (see Fig. 2), referred to as frequency-division multiplexing. Although multiband communication requires a shorter equalizer for each subband, it may be inefficient in using the bandwidth or spectrum because usually it requires extra space or guard bands to keep the parallel modulated carriers from interfering with one another. The objective of this paper is to compare single wideband and multiband transmissions using experimental data.

![FIG. 1. (Color online) (a) Schematic of the KAM11 communications experiment. A 16-element VRA was deployed in 106 m deep water. The middle element at 61.6 m depth from an 8-element source array suspended from R/V Kilo Moana was used for both multiband and single wideband transmissions. (b) CIR estimated from the LFM probe (10 to 32 kHz) received by the VRA.](image-url)
subbands with each bandwidth 4.5 kHz, centered at 12, 18, 24, and 30 kHz, respectively. A raised cosine filter was used as a shaping pulse with an excess bandwidth (or roll-off factor) of 12.5% resulting in a relatively sharp transition. The spectrum of the four shaping filters is shown in Fig. 2 (solid line). The symbol rate for each subband was $R = 4$ ksymbols/s for binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK) modulations with each data packet duration of 4.3 s.

The single-carrier communication signals employed a raised cosine filter with an excess bandwidth of 100% and carrier frequency of 22 kHz as superimposed in Fig. 2 (dashed line).

Note that the spectral shape effectively excludes use of the band on both edges. Five different data packets with various modulations were concatenated together to form a single multi-packet transmission with a duration of about 1-min and the order of the packets was [BPSK, QPSK, 8-QAM (quadrature amplitude modulation), 16-QAM, 32-QAM]. With the symbol rate of $R = 12$ ksymbols/s, the corresponding data rate is 12, 24, 32, 48, and 60 kbits/s, respectively. Each data packet was 9.4-s long including a LFM channel probe in the preamble. The 1-min long signal was repeatedly transmitted every 2 h from the source at a 61.6-m depth for an extended period of time. In this letter we will analyze a total of three sets of single-carrier communication data packets (i.e., 04:27, 06:27, and 08:27 UTC) transmitted within 2 h from the multiband transmission (06:16 UTC) reported in Ref. 7 including the one closest (i.e., +10 min).

IV. PERFORMANCE ANALYSIS

For single-carrier, wideband processing, the TR-DFE exploiting the sparse nature of the channel was employed since it was shown to provide the best performance and robustness in a similar environment. A similar TR-DFE was also applied to multi-carrier communication in Ref. 7. To accommodate the time-varying channel, the TR-DFE was implemented on a block basis while the sparse channel estimation is done using the matching pursuit (MP) algorithm. In particular, the MP channel estimates used $N_T = 600$ training symbols for the first block, and in the subsequent blocks the most recent $N_T$ decoded symbols (decision-directed) were used for channel updates with a block size of $N_B = 2000$ (i.e., 167-ms). The recursive least squares algorithm was employed as an adaptive DFE with a forgetting factor of $\lambda = 0.998$. The number of feedforward and feedback filters were 80 (40 symbols) and 40, respectively, where the feedforward filters are fractionally spaced (i.e., $T/2$).

The performance of single-carrier communication is summarized in Fig. 3 compiling all three data sets with various modulations collected less than 2 h from the multi-carrier transmission. The horizontal axis (bits/symbol) corresponds to BPSK, QPSK, 8-QAM, 16-QAM, and 32-QAM modulations, respectively. The average performance is about 18 dB in terms of output SNR. However, the performance tends to degrade with an increase in bits/symbol from BPSK (2) to 32-QAM (32). This is not surprising due to the density of the constellation and increased sensitivity to phase errors for higher-order constellations. In comparison, the first three sub-bands in multiband communication achieved on average about 13 dB (see Table II of Ref. 7) while the fourth subband (rightmost in Fig. 2) occupying the high frequency region (28 to 32 kHz) yielded only about 7 dB, much less than 13 dB.

The poor performance of the fourth band (28 to 32 kHz) was ascribed to a combination of strong attenuation (propagation effect) and weak transmit characteristics of the projector in that frequency region (~4 dB lower) such that the average input SNR over the VRA was reported about 8 dB lower than in the other subbands. For a complete picture, a noise spectral density plot is shown in Fig. 4 from signal-free data on the VRA during the KAM11 experiment (06:55 UTC). The noise spectral density decreases with an increase in frequency, approximately 10 dB from ~47 dB (10 kHz) to ~37 dB (32 kHz). The spectral bump at 3.3 kHz (acoustic) and spike at 33 kHz (likely a data acquisition system artifact) are outside of the bandwidth of interest (10 to 32 kHz).

Finally, the aggregate data rate for multi-carrier transmissions including the fourth band was reported as 16 and 32 kbits/s, respectively, for BPSK and QPSK modulations with less than a 0.5% bit error rate (BER). In comparison, Fig. 3 demonstrates that single-carrier communication can achieve a higher data rate of 48 kbits/s for 16-QAM (almost error-free) and up to 60 kbits/s for 32-QAM with less than...
mated channel impulse responses (06:16 UTC) at the same identified over a 4-ms delay spread. In comparison, estimation bandwidth (10 to 32 kHz), there are 4 distinct, sparse arrivals for a receiver at 71.15 m depth (Ch. No. 8). Using the large sequence of symbols (training mode) is displayed in Fig. 5 based on the least mean-squares algorithm using the known diversity. The temporal evolution of the CIR (06:27 UTC) with bandwidth which in turn can translate into additional diversity and is characterized by a q-function. A measure of temporal compression, since the sidelobe level of the q-function reduces with channel complexity.

V. SUMMARY

Single- and multi-carrier communication approaches were compared using data collected from the KAM11 experiment. The multiband communication approach divided the entire frequency band (10 to 32 kHz) into four small subbands each with a bandwidth of 4.5 kHz and achieved a data rate of 32 kbits/s with QPSK at 3-km range. Single-carrier communication data with various modulations also were analyzed, achieving a data rate of up to 60 kbits/s with 32-QAM. While both approaches were not optimized for the best performance, the simple comparison indicated that a single wideband approach can be beneficial in terms of spectral efficiency with modest computational complexity using a TR-DFE. A plausible explanation was that an increase in diversity with the use of wideband transmissions enables resolving more multipath components. From the TR perspective, the increased channel complexity leads to an improved q-function behavior, resulting in performance enhancement.

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FIG. 4. (Color online) Noise spectral density observed on the 16-element VRA. For the frequency band of interest (10 to 32 kHz), the noise level decreases with an increase in frequency, approximately 10 dB from 47 dB (10 kHz) to 37 dB (32 kHz).

FIG. 5. (Color online) Temporal evolution of the channel impulse response at the VRA element #8 (71.15 m) for a single-carrier transmission (10 to 32 kHz). There are 4 distinct arrivals identified over a 4 ms delay spread as compared to just 2 arrivals with a smaller bandwidth of 4.5 kHz (see Fig. 3 of Ref. 7).