Improved Multipath Robustness of DFH Modulation in the Underwater Acoustic Channel

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***Abstract*—We characterize performance improvement of differential frequency hopping modulation under two techniques that mitigate the multipath effects of the underwater acoustic channel: blind adaptive equalization and beamforming. We report results on data collected at-sea during the RACE08, SPACE08 and WHOI09 experiments, and show that the bit-error rate improves with the application of these two techniques. Future improvements may combine joint single-element, blind equalization and beamforming (multi-element) approaches to leverage their respective strengths.**

I. Background on DFH Modulation

Differential frequency hopping (DFH) is a frequency hopping digital signaling technology that achieves the desirable performance features of non-interfering spread spectrum operation, spectral reuse, multipath fading mitigation, and interference resistance [1]–[3]. DFH waveforms were originally proposed for operation in terrestrial HF (High Frequency) bands [1] and later generalized to any frequency range [2]. Generalized DFH waveforms have demonstrated excellent single-user performance in additive white Gaussian noise and Rayleigh fading channels, and robustness to co-channel (multi-user) interference. DFH has been favorably compared to conventional FSK, Fast Frequency Hopped MFSK (FFH/MFSK), and Direct Sequence Spread Spectrum (DSSS) [2], [4], [5].

For DFH waveforms, the frequency of the transmitted tone depends on both the current data symbol and the previous transmitted tone. That is, given a data symbol X_n and the frequency of the previous hop F_{n-1}, the frequency of the next hop is determined as $F_n = G(F_{n-1}, X_n)$ where the function G can be viewed as a directed graph – that is a *trellis* – whose nodes correspond to the set of possible frequency values taken on by F_n. For a DFH system with hop set size M, F_n takes on one of M possible values $\{f^1, f^2, \dots f^M\}$.

Trellis models, often used in depicting and analyzing convolutional codes, are easily applied to a differential frequency-hopped signal. Fig. 1 shows an illustrative example for the case of $M = 4$. The nodes on the vertical axis of the trellis correspond to the set of all possible frequencies $\{f^1, f^2, f^3, f^4\}$ transmitted by the system at hop $n-1$. Branches leaving each state terminate at the frequencies that are allowed at the next hop n, according to the trellis $G(F_{n-1}, X_n)$. A label $\{0, 1\}$ on each branch indicates the encoded bits that correspond to the transition from the current transmitted frequency F_n to the next transmitted frequency F_{n+1}. For the trellis in Fig. 1, the bit rate is one bit per hop, and the data sequence shown by the dotted line is 0110. Note that the trellis path visits node $f3$ twice: the first detection at hop index $n = 2$ corresponds to a '0' data bit and the second detection at $n = 4$ corresponds to a '1' data bit. This illustrates the defining characteristic of DFH: the *sequence* of detections, not the detections themselves, carry the information. Thus, trellising endows the DFH receiver with the built-in capability to recover transmissions that are missing due to a fading channel or collisions with interferers.

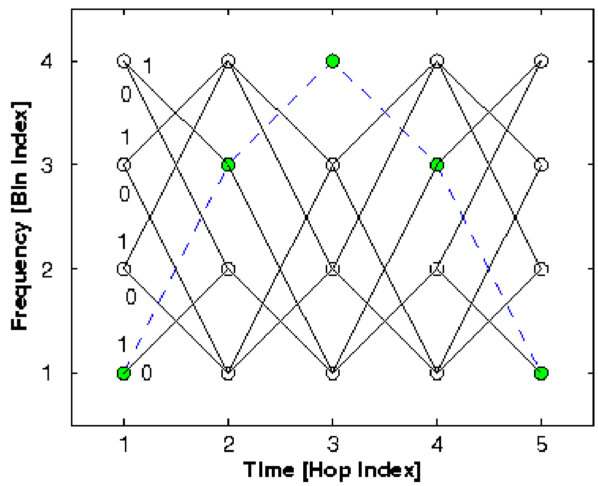

Fig. 1. Example DFH trellis for a hop set of size $M = 4$. Frequency bin f^3 is visited twice, but each time a different bit is present, illustrating the DFH property that the sequence of detections contains the information.

Because the DFH waveform is tolerant of interfering signals, it is well suited for multiple access applications where multiple users simultaneously transmit in an uncoordinated fashion, thus interfering with each other. In a multi-user DFH system, each user u transmits according to its own unique trellis G_u. The multi-user DFH receiver disambiguates the simultaneous-users transmissions by following each user u with its corresponding trellis G_u. This process is illustrated

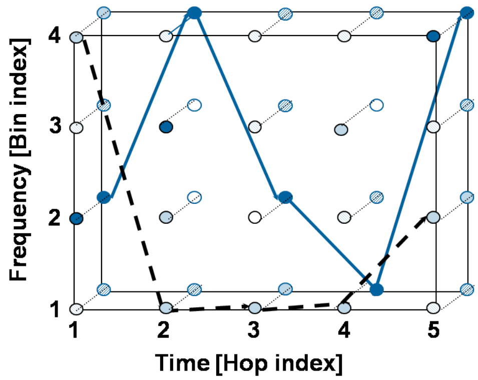

Fig. 2. Example two-user decoding. The two trellises are represented on parallel planes and the hop sequences with dashed and solid lines. At hop index $n = 4$, the two users simultaneously transmit the same frequency, potentially causing reception errors. However, the transmission is correctly decoded because each user's transition is governed by a separate trellis.

in Fig. 2 for the case of two users.

DFH modulation is also self-synchronizing. Because the data are encoded in the intervals between successive hops, both bulk frequency and time offsets can be determined in the decoder from the waveform itself, without the use of training symbols. Furthermore, the described approach does not rely on centralized controllers, and requires no orchestration between users for conferencing and bandwidth packing, beyond the assignment of each user's trellis G_u.

The underwater channel presents difficult challenges to acoustic communication schemes. Waveforms propagating in the underwater channel can be severely distorted in both time and frequency, causing a wide range of multipath and Doppler effects. Multipath receptions are the primary cause of inter-symbol interference (ISI) in the underwater acoustic channel. For FSK-type waveforms, this phenomenon causes energy transmitted in one time-frequency bin to extend further in time than the intended duration of that bin. Doppler spreading has a related effect in that energy from one time-frequency bin can leak into neighboring frequency bins at a given time instant. Furthermore, the frequency fading characteristics of the underwater channel may cause the energy in some time-frequency bins to be drastically attenuated relative to other bins.

In previous work, the authors demonstrated the capabilities of DFH modulation for underwater acoustic communications [6]. A single-hydrophone, auto-synchronizing, baseline demodulation algorithm showed considerable promise for single- and multi-user scenarios, in both simulations and on data collected during at-sea experiments. Additional processing enhancements aimed at mitigating channel-induced fading and multi-user interference further improved the performance in follow-on work [7].

In this work we describe two further enhancements to the DFH demodulation chain aimed at reducing the ISI due to severe multipath conditions. First, we describe a blind equalization approach to mitigate severe ISI on single-hydrophone receptions. Then, we describe a simple multi-element combining approach that exploits the availability of multiple hydrophones.

II. Blind Equalization for DFH

Blind equalizers (i.e. equalizers that do not rely on training sequences) are ideally suited for DFH modulation, which does not rely on training symbols to estimate the channel effects. Among blind equalizers, the well-known constant modulus algorithm (CMA) equalizer has been extensively studied [8]–[10]. Originally designed for terrestrial PSK communications, CMA equalization has also been shown effective for terrestrial FSK-type modulations [11], [12] which also have the property of constant modulus (amplitude).

In the underwater channel, DFH signals, like other FSK signals, may lose their the constant modulus property due to multipath reflections, which cause variations in the amplitude of the receptions . In previous work, we showed through simulations how environments characterized by hard seafloors and smooth water surfaces pose a particular challenge to DFH, which is otherwise very robust to mild-to-intermediate multipath [6]. Here we address severe multipath with the CMA equalizer. We adapt the approach in [11] to the underwater case, and place a CMA equalizer in front of the DFH demodulator, operating at baseband, as in Fig. 3.

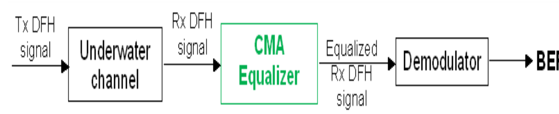

Fig. 3. Baseband signal processing chain with an equalizer module.

The CMA adaptively and iteratively trains the coefficients $\mathbf{c}$ of the equalizer by gradient descent. The coefficients at iteration $k+1$ are computed according to the update rule:

$$\mathbf{c}_{k+1} = \mathbf{c}_k - \mu E\left[\frac{\partial D}{\partial \mathbf{c}_k}\right], \tag{1}$$

where the error function D is the distance between the magnitude (or modulus) of a received symbol sequence Z_i and a data-dependent constant R,

$$D = \left(|Z_k|^2 - R\right)^2. \tag{2}$$

Rule (1) finds the optimal coefficients $\mathbf{c}^*$ that minimize D, thus restoring, in a lest square sense, the constant modulus property to the received DFH signal. Thus the interference from the multipath receptions is attenuated, reducing the negative impact of ISI on the decoded bits.

We tested our CMA-based equalization approach in a series of preliminary simulations. Using the Sonar Simulation Toolkit (SST) [13], we simulated the transmission of DFH waveforms spanning a bandwidth of 4 kHz at a carrier frequency of 15 kHz in a severe-ISI underwater channel. An equalizer of length 1024 taps applied to the received signal and the resulting equalized signals were decoded. The bit error rate (BER) for the equalized case dropped from order 10^{-2} without equalization to order 10^{-3} with equalization, demonstrating the validity of the approach. Fig. 4 shows the physical improvement in performance due to equalization. Channel impulse responses (CIRs) are plotted for the difficult case of severe ISI. Note how the multipath peaks are significantly attenuated in the equalized case, leading to much milder ISI and thus to improved performance.

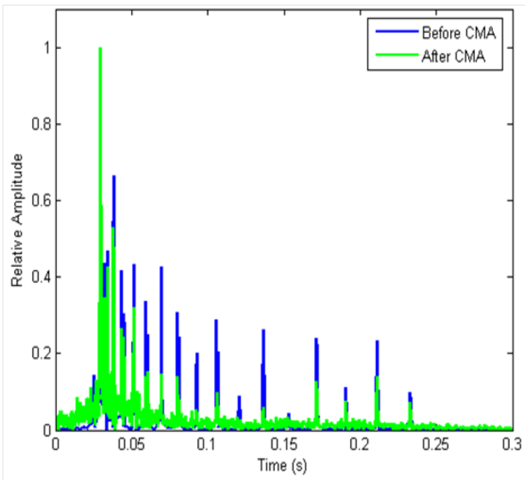

Fig. 4. CIRs before and after equalization. The multipath returns, which contribute to ISI, are noticeably attenuated.

III. Beamforming for DFH

A non-coherent multiple channel combining procedure takes advantage of the spatial diversity available in the collected datasets. Synchronization is performed on each channel independently. One of the output products of the synchronization is a bit sequence. These bit sequences are cross-correlated between the channels to be combined. If the peak cross-correlation falls below a threshold, the second channel is dropped. Otherwise, the two spectrograms are aligned and summed incoherently with equal weights before demodulation is performed.

IV. Experimental Results

In this section, we report performance results for the blind equalization and beamforming approaches on experimental data.

A. Equalization Results for RACE08 and SPACE08

We quantify the performance improvement provided by the equalization by computing BERs for the RACE08 and SPACE08 sea experiments. The experimental layout for the RACE08 sea trial was described in detail in previous work [6], [7]. During the RACE08 experiment, multiuser DFH sequences were transmitted in Narragansett Bay, Rhode Island from 1-17 March 2008, The corresponding received sequences were recorded and analyzed. The sound speed profile was approximately isovelocity, varying with the tides (primarily due to salinity changes) between 1455 and 1470 m/s. The surface conditions were primarily windblown chop. Much of the bottom type found in the Bay system is clay-silt or sand-silt-clay [14]; in either case, a relatively soft bottom. The transmitted DFH signals spanned the 9-13 kHz bandwidth. For this combination of signal characteristics and environmental conditions, we expect multipath effect on the received waveforms to be mild.

We note that although the experimental setup included receiver arrays, no array processing was done for the equalization processing on the received DFH signals. Each receiver hydrophone was treated as an independent transmission, and the error rates on all single-hydrophone transmissions were averaged together to estimate the overall BERs.

The equalizer consists of a 1024-tap finite impulse filter, operating at the symbol rate, effectively spanning 16 symbol periods (256 ms). Fig. 5 shows comparisons of BERs for non-equalized and equalized signal receptions for user no. 4. Data points above the diagonal represent an improvement due to equalization. Note that for a few transmissions the performance decreases, due to a mismatched choice for the adaptation constant μ (which was set to 10^{-6}) . However, the overall trend is toward performance improvement.

It is interesting to test the CMA approach in a multiuser environment, where the additional users act as interferers and compound the deleterious effects of the multipath environment. Fig. 6 shows the BERs for user no. 4 when all four users are transmitted simultaneously. It is surprising that equalization improves the BER also for the case when multiple users are transmitted simultaneously. This is because the receiver first attempts to synchronize the reception to each of the four possible users, and then applies CMA equalization to each user separately. Effectively, each user's bit stream is synchronized and equalized individually while treating the other users as additive interference. For the RACE08 experiment, which exhibits benign environmental conditions with limited multipath, this strategy works well.

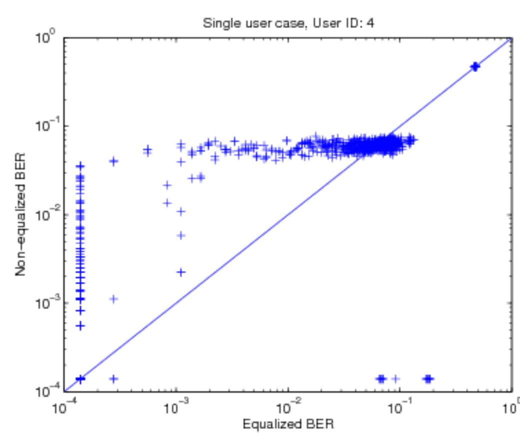

Fig. 5. Single-user BER comparison for RACE08 user no. 4 transmissions. Points *above* the diagonal indicate an improved BER due to equalization.

Table I summarizes the results for RACE08 in terms of BER and the proportion of error-free transmissions, which is another commonly-used metric for performance comparison.

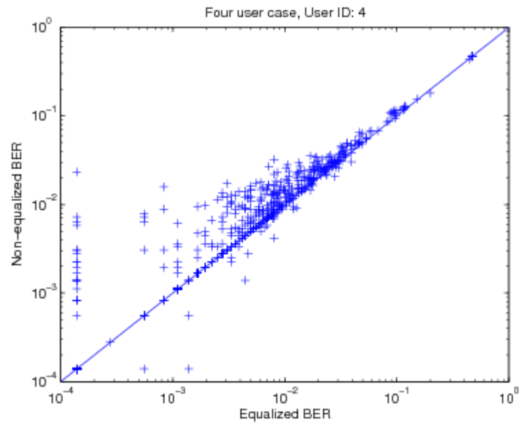

Fig. 6. Multi-user BER comparison for RACE08 user no. 4 transmissions. Points *above* the diagonal indicate an improved BER due to equalization.

The reported averages are slightly pessimistic because they include processing results for non-DFH signals: during the experiment, non-DFH signals were mis-labeled as DFH transmissions. These signals appear as BER of 50% (upper tight corner) in Fig. 5 and Fig. 6 and skew the averages in Table I, so that the actual improvement due to equalization is higher than that shown. The median BER results attempt to filter out these mislabeled cases.

TABLE I
RACE08 EQUALIZATION RESULTS: PERCENT IMPROVEMENT IS IN PARENTHESES.

No. users	Parameter	CMA	no CMA
1	Average BER	0.0232 (6.83)	0.0249
	Median BER	0.0001 (–)	0.0001
	% error-free	68.80 (8.8)	63.23
2	Average BER	0.0262 (4.38)	0.0274
	Median BER	0.0015 (54.5)	0.0033
	% error-free	47.03 (20)	39.15
3	Average BER	0.0687 (4.98)	0.0723
	Median BER	0.0610 (6.44)	0.0652
	% error-free	4.96 (–)	4.96
4	Average BER	0.0276 (7.69)	0.0299
	Median BER	0.0130 (1.45)	0.0152
	% error-free	21.23 (11.2)	19.09

SPACE08 was conducted at the Air-Sea Interaction Tower (ASIT), which is part of WHOI's Martha's Vineyard Coastal Observatory (MVCO), between October 13-28, 2008. The surface conditions during the trials were primarily wind blown chop and the sound speed profile was approximately isovelocity. The topography in the area is relatively benign with some transient small-scale features that are generated by passing storms. The bottom type at the experiment location is sandy. Following the passage of the first major storms of the season, the water column tends to stay well mixed for the winter resulting in a constant sound speed as a function of depth. At times during the experiment duration, winds reached high speeds, causing increased variability in the acoustic channel characteristics.

For SPACE08 there were no single-user transmissions, so the equalizer and DFH decoder operated in the presence of interfering users for all transmissions. As in the RACE08 experiment, no array processing was employed at the receiver, and all receptions on individual hydrophones were processed by single-user demodulation. Performance on the SPACE08 experiments mirrors the RACE08 results, as shown in Table II. Equalization improves both the average and median BERs. The underwater acoustic channel for SPACE08 appears to be more benign that for RACE08, so the performance gain due to equalization is not as dramatic, while still providing benefits. As the number of simultaneous users increases, multi-user interference becomes the dominant effect over multipath, and the benefits of equalization are diminished.

TABLE II
SPACE08 EQUALIZATION RESULTS: .

No. users	Parameter	CMA	no CMA
2	Average BER	0.0010 (23.08)	0.0013
	Median BER	0.0003 (40)	0.0005
	% error-free	0 (–)	0
3	Average BER	0.0039 (7.14)	0.0042
	Median BER	0.0024 (7.69)	0.0026
	% error-free	6.59 (8.6)	6.07
4	Average BER	0.0192 (2.04)	0.0196
	Median BER	0.0105 (1.87)	0.0107
	% error-free	3.38 (4.3)	3.24

B. Hydrophone element combining results for SPACE08 data

Hydrophone element combining results for the SPACE08 data are shown in Table III, in terms of proportion of trials with zero errors. The fading mitigation procedure [6] has been employed for both single element and combined element results. The fading mitigation improves performance for both single element processing and combined element processing. Combining element signals results in dramatically improved performance for almost all cases. The exception is user 2 of 2 on the SE receiver at 200m range: single element results are 33% error-free, while combining elements results in 29% error-free receptions. This slight performance penalty in a single case is offset by the dramatic improvements: for instance, user 1 of 3 on the SW receiver at 200m range has no error-free receptions with single-element processing, but combining elements results in 94% error-free receptions.

C. Hydrophone element combining results for RACE08 data

The single element that most often had the lowest error (the surfacemost element) is compared to the combined-element result in Fig. 7. All array elements are combined, and are synchronized to the surfacemost element. The array at 400m range has 24 elements; the array at 1000m range has 12 elements. The predominance of points below the diagonal demonstrates the dramatic improvement noncoherent array element combining yields. These results are restricted to the cases where a legitimate DFH signal was transmitted.

D. Hydrophone element combining results for WHOI09 data

For the WHOI09 experiment, we transmitted a 20kHz signal, which is wider than the "flat" portion of the transmitter

TABLE III
SPACE08 ARRAY ELEMENT COMBINATION RESULTS: PROPORTION OF TRIALS WITH ZERO ERRORS

Array Location	SE 60m		SW 60m	
No. elements	1	2	1	2
user 1 of 2	92%	92%	74%	99%
user 2 of 2	32%	85%	46%	55%
user 1 of 3	70%	80%	20%	88%
user 2 of 3	0%	69%	2%	80%
user 3 of 3	11%	83%	18%	95%
user 1 of 4	43%	94%	4%	95%
user 2 of 4	11%	73%	1%	57%
user 3 of 4	0%	25%	0%	23%
user 4 of 4	0%	69%	5%	80%
Array Location	SE 200m		SW 200m	
No. elements	1	2	1	2
user 1 of 2	46%	99%	22%	98%
user 2 of 2	33%	29%	9%	95%
user 1 of 3	0%	95%	0%	94%
user 2 of 3	8%	88%	0%	88%
user 3 of 3	44%	98%	38%	63%
user 1 of 4	4%	96%	2%	95%
user 2 of 4	0%	71%	0%	54%
user 3 of 4	6%	42%	6%	75%
user 4 of 4	24%	85%	24%	93%
Array Location	SE 1000m		SW 1000m	
No. elements	1	2	1	2
user 1 of 2	67%	81%	50%	83%
user 2 of 2	25%	56%	25%	75%
user 1 of 3	47%	61%	56%	76%
user 2 of 3	5%	47%	3%	52%
user 3 of 3	3%	48%	0%	38%
user 1 of 4	33%	90%	23%	83%
user 2 of 4	8%	46%	11%	50%
user 3 of 4	5%	14%	6%	26%
user 4 of 4	6%	23%	7%	24%

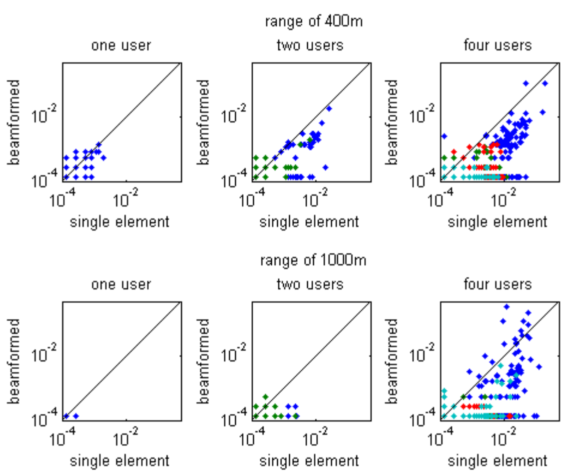

Fig. 7. Pointwise comparison between single-element and combined-element (beamformed) bit error rates. Points *below* the diagonal indicate an improved BER due to multi-element combining.

(imparting a 7dB variation across the band), and experiences a 5.2dB variation in volume attenuation across the band. The signal amplitude tapered by 20dB from the beginning to the end of the transmissions. The experiment collected twelve single-user receptions (three at 1km range, nine at 2km range), and six multi-user receptions (three at 1km, three at 2km). The multi-user receptions consisted of three users transmitting independently from three elements on the source array. All receptions were collected on 7 December 2009, on four receive channels. There was no environmental instrumentation. The water depth was 15.5m, and the surface conditions were calm (<0.3m).

The best single channel overall is compared to results for combined channels. For the twelve single user trials, there were no errors, neither for the best single channel nor for the combined channels. Our error-free single-user performance demonstrates DFH's robustness to fading, whether environment- or equipment-related. The results for the multiuser trials are shown in Table IV. Combining element signals resolves almost all errors.

TABLE IV
WHOI09 ELEMENT COMBINATION RESULTS: BIT ERROR RATES

time	range	user	single element	combined elements
194800	1km	1	1.25%	none
		2	5.46%	0.04%
		3	0.45%	none
194930	1km	1	6.20%	0.11%
		2	30.74%	0.03%
		3	0.26%	none
195060	1km	1	21.46%	0.20%
		2	40.05%	1.14%
		3	0.26%	none
194800	2km	1	none	none
		2	4.94%	none
		3	5.37%	none
194930	2km	1	none	none
		2	2.26%	0.01%
		3	3.01%	none
195060	2km	1	none	none
		2	0.99%	0.01%
		3	3.23%	none

V. Discussion and Future Directions

The simple element combination used is preferred over traditional coherent beamforming in cases where the angle to the source is unknown or poorly defined due to shallow-water modal propagation. In contrast to traditional adaptive techniques, it requires no training symbols.

Future research must address MAI in scenarios similar to the SPACE08 experiment, where tougher environmental conditions make it more difficult for the receiver to synchronize to each user's transmission and thus limit the benefit provided by equalization.

VI. Acknowledgement

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