High-Frequency FH-FSK Underwater Acoustic Communications: The Environmental Effect and Signal Processing

Wen-Bin Yang and T. C. Yang

Naval Research Laboratory
Washington DC 20375, USA

Abstract. This paper analyzes the environmental effect and signal processing approaches for frequency-hopped frequency-shift-keyed (FH FSK) underwater acoustic communications based upon data collected in two experiments: the RDS4 experiment near Halifax, Canada and MREA03 experiment near Elba, Italy. The FH FSK signals have a bandwidth of 4 kHz centered at 17 and 20 kHz. The source was towed at ~4 knots. The signals were received on a vertical line array anchored to the bottom. The acoustic environments at both sites have the same downward refractive sound speed profiles but very different bottom properties. The multipath spread last ~20 msec in the MREA03 experiment and is > 1 sec in the RDS4 experiment. The different lengths of multipath delays have a significant effect on the bit error rate (BER) and the appropriate signal processing needed to reduce the BER. We present the data analysis results, the signal processing approaches, including multi-channel beamforming and spatial diversity combining, and discuss the implications for the use of FH-FSK for multi-user communications.

INTRODUCTION

Underwater acoustic communications (ACOMM) are required for command, control and networking of autonomous underwater vehicles (AUVs). For multiple users, networking between users requires multi-access communications due to latency in signal transmission, particularly when AUVs are spread out in different ranges. Two signaling approaches using spread-spectrum are the frequency-hopped and direct sequence methods, known as the frequency-hopped frequency-shift-keying (FH FSK) and Direct Sequence-Code Division Multiple Access (DS-CDMA) modulation schemes [1]. DS-CDMA spreads the information bits in different codes and is subject to near-far problem as the signal can be degraded by nearby interference sources. It has the advantages of higher processing gain through code compression. FH FSK spreads the information bits in different frequency bins. To minimize the number of times that different users transmit in the same bands (frequency collision), a common approach is to use a prime number of frequency bins and assign a hopping pattern, which increments through the frequency set by n where n is the user number [2]. In this manner, any pair of users will occupy the same frequency bin only once per hopping pattern. To reduce the bit errors due to collisions between different users, one resorts to the use of an appropriate error-correction code. We concentrate on FH FSK in this paper.

The performance (e.g., bit error rate) of the FH FSK signaling approach depends on the signal design and the acoustic channel characteristics in which it operates. To maximize the number of users, the number of frequency bins should be large. In principle, the tone duration should be long with respect to the channel clearing time (the channel multipath spread) so that there is little signal beyond the symbol period. This results in many narrow bands, which are subject to frequency selective fading, and are vulnerable to uncertainty in the Doppler shift. To minimize the sensitivity to Doppler shift, a wider frequency bin (larger than the expected uncertainty in the Doppler shift estimation) can be used. This minimizes the frequency selective fading but the drawback is the signal energy exceeding the symbol duration (inter-symbol interference) unless a sufficient guard time is built into the signal design. Also bit error rate increases due to frequency collision, as a small number of frequency bins are available. The performance of FH FSK clearly depends on the multipath delay time and the ability to estimate the Doppler shift.

For a single user, the transmitter can select any hopping pattern, which hops through the (selected) frequency bins only once per hopping pattern. The total duration of the hopping sequence needs to exceed the (maximum) multipath delay.

In this paper, we study the FH FSK signaling performance for a single user under two very different shallow water environments: one with a multipath delay of ~20 msec and the other with a multipath delay >1 sec at 18-20 kHz. The source was towed at a speed of 4 knots in both cases. The uncoded bit-error-rates (BERs) are determined as a function of the signal-to-noise ratio using the conventional approach, which detects the signal within one-symbol duration. As expected, BER is significantly higher for the second case than the first case. To reduce the BER a modified algorithm is presented. Implications for multi-users are discussed.

ENVIRONMENTAL EFFECT AND SIGNAL DESIGN

Environmental impact on the FH FSK signaling performance is studied using two experimental data sets: one from the MREA03 (Military Rapid Environment Assessment) experiment which was conducted in June of 2003, in water of ~103m depth north of Elba, Italy, and the other from the RDS4 (Rapidly Deployable Systems) experiment which was conducted off the coast of Halifax, Canada in water of ~80m depth. A vertical line array of 8 receivers was used in both experiments. The source was towed behind a ship at 4 knots. The FH FSK signals covered a range of 18-22 kHz and 16-20 kHz in MREA03 and RDS4 experiments respectively.

Environmental Effect

The signal characteristics are very different between the MREA03 and RDS4 environments. In the MREA03 environment, the multipath delay spread is around 20 msec as shown in Fig. 1a. In contrast, one finds a multipath delay lasting more than 1 second in the RDS4 experiment area as shown in Fig. 1b. The differences between the multipath delay time are due to the different bottoms' absorption coefficients. The

RDS4 area has very thin sediment overlay a hard bottom resulting in a low loss environment for acoustic propagation.

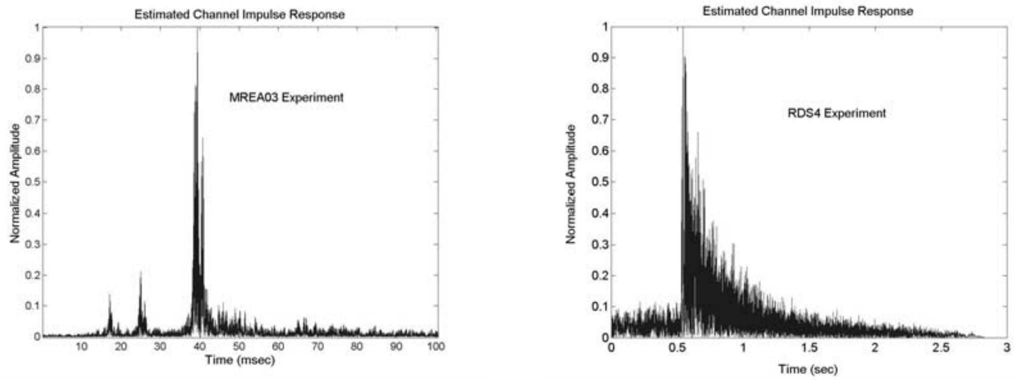

FIGURE 1. Estimated Channel Impulse Response functions. 1a: MREA03 (left figure) and 1b: RDS4 (right figure).

Fig. 2a shows the Doppler shift of the signal measured using the pilot tones, which are located outside the frequency band of the FH FSK signal. Fig. 2b shows the variance of the Doppler shift over 6 minutes, where the Doppler shift is 40.5 ± 0.5 Hz. The Doppler shift estimate is used to adjust and realign the frequency bins of the FH FSK symbols. Precise Doppler shift estimation is needed for symbol synchronization (e.g., determine the beginning of the signal).

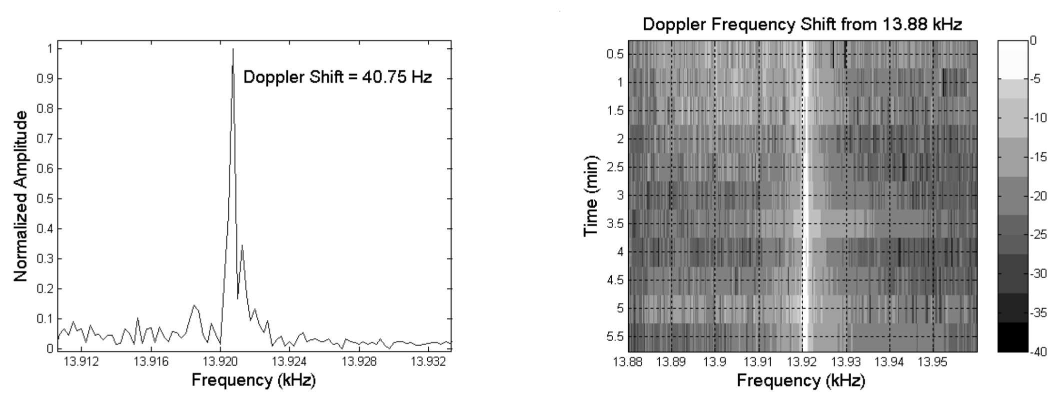

FIGURE 2. Doppler Frequency Shift Estimate**.** 2a: at a time instant (left figure) and 2b: vs. time (right figure).

FH FSK Signal Structure

The FH FSK packet is structured as shown in Fig. 3, which includes a Linear Frequency Modulation (LFM) signal, followed by the synchronization bits (also used for user identification) and then data messages with gaps between them. Two pilot (narrowband) tones outside of the FH FSK frequency bands are added to the signal to estimate the Doppler shift. An LFM signal is appended to the end of the packet. The LFM signals are used to estimate the channel impulse response functions and also the

Doppler shift, by way of the signal dilation. Either LFM or synchronization bits can be used for symbol synchronization/acquisition. The synchronization bits and data messages are modulated using FH-FSK signals with a pre-determined hopping frequency pattern.

Gap 0	LFM	Gap 1	Sync	Gap 2	Data	Gap 3	LFM	Gap 4

FIGURE 3. FH FSK Frame Structure

For both experiments, the FH FSK signals are patterned after the WHOI design [3] as opposed to the Benthos design [4]. The signal structure is shown in Table 1. Also shown is the Benthos signaling parameters for comparison. Note that both signaling schemes use the same bandwidth. Benthos scheme allows more frequency blocks and hence more users. On the other hand, WHOI's scheme yields a bit rate >4 times higher than the Benthos scheme (for a single user). Since its symbol duration is one twelfth of that of the Benthos signal, it is more prone to multipath induced symbol interference (or frequency collision) when the multipath delay is much longer than the symbol duration. In other words, the multipath effect is expected to be stronger on the WHOI signals than the Benthos signal. (Table 1 shows the trade off in the signal design.) The effects will be studied below.

TABLE 1. Comparison of WHOI vs. Benthos FH-FSK Signal Parameters

	WHOI	**Benthos**
M-ary FSK	M=2	M=8
Bandwidth	4 kHz	4 kHz
Frequency Resolution	160 Hz	11.3 Hz
# of Frequency Blocks	13	43
Symbol Duration	12.5 msec	150 msec
Guard Time	0	150 msec
Information Bits	800	102
Packet Length	29.425 sec	16.2 sec
Information Rate	27.2 bps	6.3 bps

It is worth noting that the frequency bin size (for both schemes) is twice the inverse of the symbol duration. This is a feature commonly adapted for FH FSK signals so that the frequency leakage from one frequency bin to its neighboring frequency bins is minimized. The feature is built in to minimize the vulnerability to the Doppler estimation error so that the frequency orthogonality is not exactly required.

INCOHERENT RECEIVER

FH-MFSK uses a sequence of M tones per hopping pattern. Thus a simple incoherent FH-MFSK energy detector [2] shown in Fig. 4 can be used efficiently to detect the signal as long as there is no interference from the multipath delay or a different user. The detector contains a bandpass filter of bandwidth (W) around the center frequency, a signal acquisition (or synchronization) processor, followed by a T-

second energy integrator (reset in the beginning of each symbol) and a comparator. The integrator is applied to the hopping frequency band. By design, T should be of the order of the symbol duration. This is the conventional processor. But in some oceans, the multipath delay may be longer than the symbol duration. In that case, the integration time T may be increased to capture the multipath arrivals. The benefit is improved BER performance. The drawback is more vulnerability to interference from other users and more noise. The comparator weighs the integrator output to determine the transmitted symbol. We shall study the BER performance by varying the integration time.

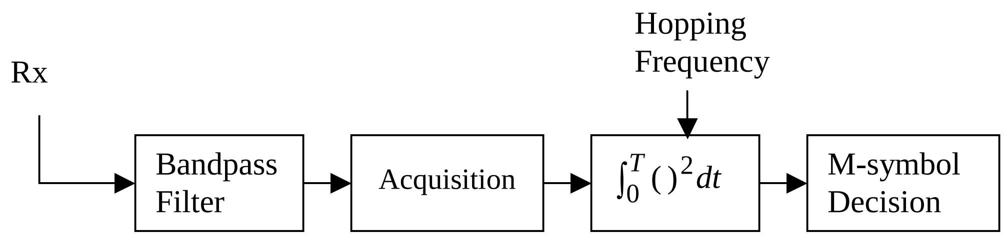

FIGURE 4. FH MFSK Energy Detector

Multiple channel signal combining methods such as beamforming and spatial diversity can also be used to improve BER performance. We use a conventional delay-and-sum (DS) beamforming technique to boost signal-to-noise ratio. We also use a spatial diversity technique of selective diversity combining [5] to lower BER value. The technique of selective diversity combining is based upon the principle of selecting the best signal among all of the signals received from different channels. The best signal is defined as the maximum signal-to-noise ratio at each pair of hopping frequencies. A combination of long integration time, beamforming and spatial diversity techniques is studied.

RESULTS AND DISCUSSIONS

The hopping pattern used in the experiments consists of 13 blocks of hopping frequencies and two frequencies within each block to represent 0 and 1. To determine the environmental impact, the uncoded BER is deduced from the experimental data. The coded BER is much smaller than the coded BER after error correction.

MREA03 Experiment

The channel impulse response function for the MREA03 environment (as shown in Fig. 1a) lasts about 20 msec. This multipath delay spread is less than two-symbol periods. Although part of the signal spreads into the next time frame, the conventional energy detector seems to work well as shown below. Eleven packets are analyzed using 8 single receivers. The source is at a range of 3.8 - 4.5 km from the receivers. Fig. 5 shows the uncoded BER of the MREA03 data. Also shown is the theoretical BER curve with only additive white Gaussian noise (AWGN). The observed BER is higher than the AWGN curve. The difference is presumably caused by the multipath induced interference. We model the (uncoded) BER data using the following formula, $p_e = \frac{1}{2}\exp\left(-\frac{\alpha}{2}\frac{E_b}{N_0}\right)$, where $\alpha = 1/\left(1+\beta\, E_b/N_o\right)$, and β represents the effective interference-to-signal ratio. For MREA03, we find β = 0.06 (-12 dB). Note that the uncoded BER over the packets is less than 9%; most of them are about 1%. When the (observed) uncoded BER is < 9%, zero BER is obtained after error decoding and correction. In this case, a 1/2 convolutional code with a constraint length of 9 is used. We conclude that the conventional energy detector (which is implemented in sea-going acoustic modems) with a single receiver yields a satisfactory result (at a range of 3-5 km) for the MREA03 environment. Consequently, there is no need to explore beamforming or spatial diversity.

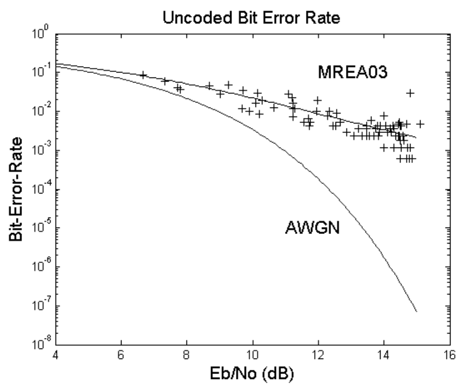

FIGURE 5. Uncoded Bit-Error-Rate: MREA03 Channel vs. AWGN Channel.

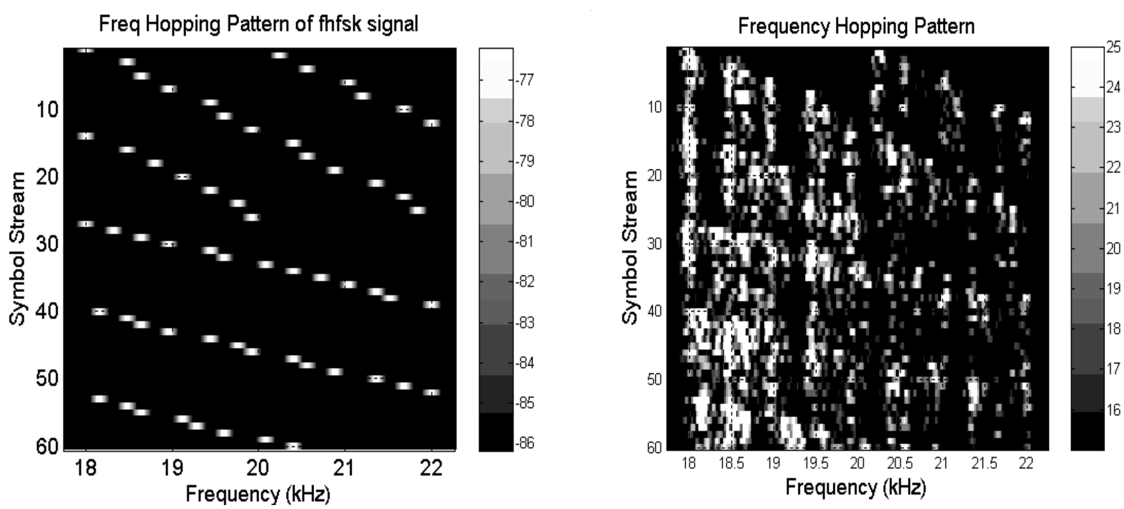

FIGURE 6. RDS4 Hopping Pattern (a) Transmit Signal (left figure) and (b) Received Signal (right figure)

RDS4 EXPERIMENT

From the RDS4 environment, the channel impulse response function (Fig. 1b) lasts more than one second, which is ~80 symbols long. Figs. 6a and 6b show the frequency-hopping pattern of transmitted and received signals at the beginning of the signal. The first 26 symbols are synchronization bits, while the others are data message bits. The synchronization bits and the data message bits were modulated using different hopping patterns in the experiment. One sees clearly in Fig. 6b a multipath delay extending over 13 symbol periods. Note that Fig. 6b displays a dynamic range of only 10 dB. The multipath spread is significantly more than 13 symbol periods when a higher dynamic range is used.

We first use a conventional energy detector to analyze the experimental data. In this case, the conventional energy detector picks up predominantly the signal energy associated with the first (main) path since the integration time is only one symbol long. Due to the severe multipaths, a much higher uncoded BER is found for the RDS4 environment (compared with MREA03) using the conventional receiver. Table 2 shows the uncoded BER values over 3 received packets. The uncoded BER is greater than 14%. For these cases, error correction does not work very well. Substantial coded BERs remain. Hence, it is necessary to modify the conventional receiver.

TABLE 2. Uncoded BER Using Conventional Energy Detector

Received Packet #	**310**	**328**	**346**
Distance from TX source	0.5 km	1.2 km	2.0 km
SNR (dB) @ Ch. #1	3.87	3.18	3.02
Uncoded BER @ Ch. #1	14.35 %	21.25%	22.02 %

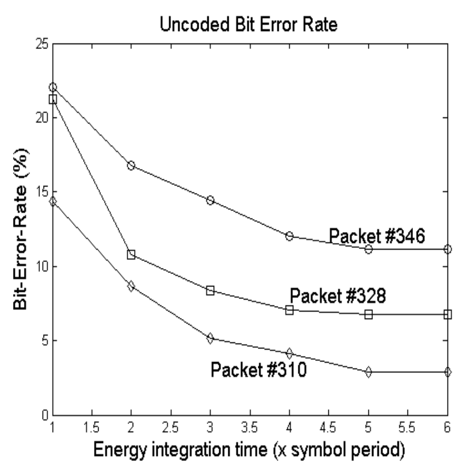

FIGURE 7. Uncoded BER vs. Integration Time

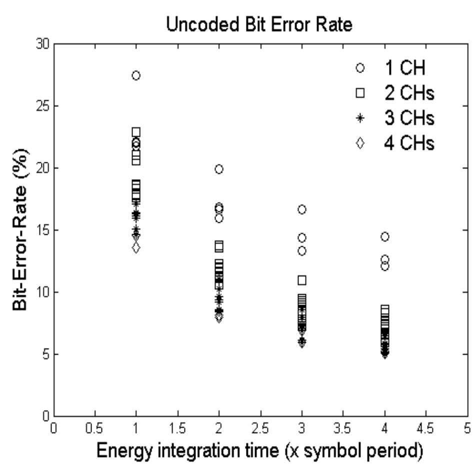

FIGURE 8. Multi-channel Combining Uncoded BER vs. Integration Time

The energy detector is modified to include a longer integration time for multipath energy combination in the same spirit as the RAKE receiver. The SNR is increased and the BER is lowered. The relationship between the uncoded BER and integration time is shown in Fig. 7. We note that the BER values are reduced dramatically as the integration time increases up to 4-symbol period. Increasing the integration time further (e.g., to include the 5th and 6th symbol periods) did not significantly improve the BER due to the decreasing signal energy in the later arrivals.

In addition to increasing integration time, we use spatial diversity and beamforming to improve BER performance. The multi-channel combining techniques are based on an example of 4-channel receivers, which are spaced at 4, 4 and 1 wavelengths. The BER results are shown in Fig. 8. One notes that the uncoded BER is uniformly reduced by ~10% using 4-channel spatial diversity or beamforming versus a single channel. For this example, we do not see any significant difference between spatial diversity and beamforming or a combination of them. We find that the original data message can be recovered perfectly (i.e., coded BER=0) when the uncoded BER is lower than 13% (using ½ convolutional code with a constraint length of 9 and interleaving schemes).

SUMMARY AND DISCUSSIONS

The BER performance of FH FSK signals is critically dependent on the signal design, namely, the symbol duration relative to the multipath delay. For environments in which the multipath delay is much longer than the symbol duration, the uncoded BER error rate can be high (>20%) using the conventional processor, which detects signal energy with a symbol period. BER can be reduced significantly by extending the signal integration to several symbol periods and using spatial diversity/beamforming, but this precludes the use of multi-users due to signal collisions. As a result, the use of FH FSK is limited to environments with short multipath delay. To remove this constraint, a method to remove the multipath spread either by a channel equalizer or passive-phase conjugation will be needed and will be presented in a separate paper.

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