A NEW MULTI-CHANNEL SPATIAL DIVERSITY TECHNIQUE FOR LONG RANGE ACOUSTIC COMMUNICATIONS IN SHALLOW WATER

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Abstract - **Underwater acoustic communication is limited to very low rates without the use of techniques that mitigate the influence of the acoustic channel. A new multi-channel spatial diversity communication scheme has been developed at Florida Atlantic University (FAU). This technique combines a novel synchronization method with a maximum-likelihood symbol estimation. The technique is tested with the FAU Dual Purpose Acoustic Modem (DPAM) which uses one transducer for data transmission and 4 hydrophones for data reception. The DPAM transmits messages using 4 types of Frequency-Hoped Multiple-Frequency-Shift-Keying (FH-MFSK) modulation: 4 hops at 221 coded bits per second (cps), 2 hops at 442 cps, or no hoping at 886 cps, or 1182 cps. The bit sequence modulated can be encoded using 3 different Error Coding Codes (ECC): a convolutional code Viterbi $7^{1/2}$, a Reed Solomon block code, or a combination of both codes. These types of modulation and encoding techniques allow for robust data transmission in adverse environment. The DPAM operates at ranges from 1 to 3 km in 50 feet of water using all 4 transducers. Such a performance can be confirmed using the model of Crepeau.**

I. INTRODUCTION

Reliable acoustic devices are needed for underwater communications between Autonomous Underwater Vehicles (AUV) and remote sensors. The underwater environment is challenging for communications. The acoustic channel creates strong amplitude and phase fluctuations of acoustic messages [1] [2] [3]. The shallow water environment is the most challenging since the waves reflect from the sea surface and the bottom of the channel differently. Multiple acoustic paths exist between the emitter and the receiver. Such a phenomenon is known as multipath [4]. The multipath results in time and frequency spread known as InterSymbol Interference (ISI). In the frequency domain, fluctuations can also be increased by a Doppler shift due to the relative motion between the emitter and the receiver [5]. Underwater the signal is attenuated by source-receiver separation, channel wave-guide characteristics and frequency-dependent absorption. Such attenuation can be characterized by the transmission loss of the signal [1] [4]. The ocean noise, due to marine life, air bubbles, and boat engines influences the received Signal-to-Noise Ratio (SNR) [6].

A new demodulation technique for long range communications in shallow water has been developed at Florida Atlantic University (FAU). The technique has been implemented on the Dual Purpose Acoustic Modem (DPAM) which operates at ranges up to 3 km. The time and frequency domain interference of the acoustic channel can be warded off by using frequency and space diversity. The space diversity is obtained by using several receivers, the DPAM uses 4 hydrophones. Thus the probability of receiving a signal with a high SNR is increased [7]. For transmission, the communication system uses a transducer with a bandwidth starting at 15.6 kHz until 31.9 kHz, and a 25 kHz center frequency. By using the Frequency Hoped-Multiple Frequency Shift Keying (FH-MFSK) modulation the deterioration of the signal in frequency domain is attenuated [8]. The system offers a choice of 4 frequency hoping modes, adapting the transmission rate depending on how much signal distortion is caused by the channel. The underlying idea is to maximize the transmission rate according to the actual channel limitations.

II. TECHNIQUES DEVELOPED

A- Synchronization

The FH-MFSK modulated message consists in a series of chirps in the time domain [9]. Each chirp contains one or several frequencies corresponding to a given bit sequence. The system reads one chirp at a time in a time buffer of duration T, corresponding to the duration of one chirp. In order to demodulate correctly a message all the energy of the chirp must be contained in the buffer. Such a process is called synchronization. The synchronization uses the correlation between the incoming chirp and the chirp expected [9]. The maximum of the correlation function corresponds to the part of the chirp containing the most energy. The synchronization consists in aligning the position of the maximum of the correlation function with the center of the buffer (Fig 1 (b) (c)). In the case of a chirp detected early, with respect to the buffer, the maximum of the correlation function is in advance of the center of the buffer. If the chirp is late, with respect to the buffer, the maximum of the correlation function is late compared to the center of the buffer.

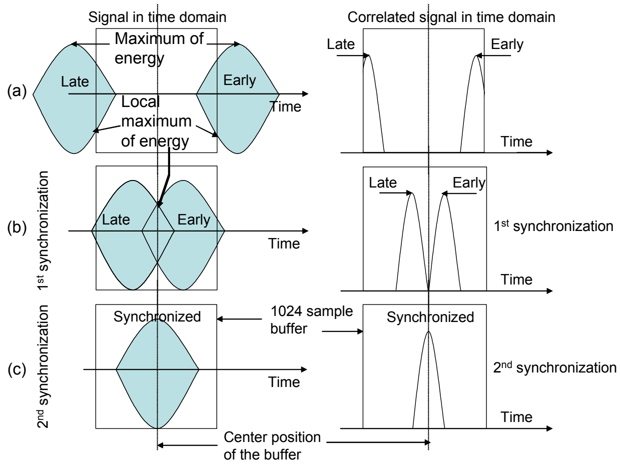

Fig. 1 Synchronization using the cross-correlation function

The synchronization on a message is achieved through a synchronization sequence, known by the receiver, of chirps at the beginning of a message. The buffer is centered on the maximum of the correlation function, Z_{ii}^k, between the i[th] incoming chirp S'_i, corrupted by the environment, and the expected chirp S_i on the channel k of the receiver. The position of the center of the buffer is then shifted to c_i, define as the average of the peak locations c_i^k of the correlation functions on each channel of the receiver:

$$Z_{ii}^k(c_i^k) = \max(Z_{ii}^k) \tag{2.1}$$

$$c_i = \frac{1}{K}\sum_{k=1}^{K} c_i^k \tag{2.2}$$

Where K is the total number of channels of the system. It can occur that the part of the chirp containing the most energy is not included in the buffer (Fig 1 (a)); the chirp is then read too late or too early. The maximum of energy on which the system synchronizes is a local maximum, and not the maximum of energy of the chirp. After one synchronization the buffer is centered on a local maximum, and the majority of the chirp energy is in the buffer (Fig 1 (b)). The system performs then a second synchronization, this time on the maximum of energy of the chirp, (Fig 1 (c)). Therefore, to avoid an inaccurate synchronization the receiver performs 2 synchronizations. Once the synchronization has been done on the sequence of Q synchronization chirps, the receiver is going to proceed to the message detection and the demodulation.

B- Demodulation

The technique used for the demodulation of FH-MFSK messages is based on a Maximum Likelihood (ML) detection [7]. On each channel of the receiver, the communication system cross-correlates the incoming chirp Fast Fourier Transform (FFT) with a bank of N matched filters corresponding to each possible frequency carried by the chirp. The system chooses the frequency of the chirp as the one corresponding to the cross-correlation function with the highest level of energy [9].

1- Message detection

The system uses the synchronization sequence to acknowledge that the incoming signal is a coded message [9]. A given number Q', $Q' \le Q$, of chirps must be detected in the correct order among the Q expected chirps for the process to identify the signal received as a message. Each chirp of the synchronization sequence carries one frequency f_i, with $i = 1,...,Q$. The maximum of the cross-correlation function on each channel k of the receiver, Z_j^k, is computed after synchronization, and is expressed as:

$$Z_j^k = Z_{ij}^k(c_j) \tag{2.3}$$

Where c_j is defined in (2.1) and (2.2), and Z_{ij}^k is the cross-correlation function between the incoming unknown chirp S_i and the expected chirp S_j on the channel k. $N = Q$ values $\{Z_j^k\}_{k=1,...,K}$ are obtained for one incoming chirp. The cross-correlation functions are averaged over the number of channels used in the array:

$$Z_j = \frac{1}{K}\sum_{k=1}^{K} Z_j^k \tag{2.4}$$

The unknown frequency carried by the chirp f_i is based on the peak estimate:

$$Z_i = \max(Z_j)_{j=1,...,N} \tag{2.5}$$

If Q' frequencies f_i are detected sequentially among the Q frequencies expected from the synchronization sequence, the detection process assumes a message is coming.

2- Demodulation

In the case of frequency hoped chirps, instead of detecting one frequency, the system has to detect the Θ frequencies carried by the chirp. The maximum likelihood is used to decide which frequency f_i^θ was carried by the chirp among the N possible frequencies of the frequency group θ, where $\theta = 1,...,\Theta$. The maximum value of the cross-correlation function on each channel k in c_j^{θ} is noted $Z_j^{k,\theta}$ and is expressed as:

$$Z_j^{k,\theta} = Z_{ij}^{k,\theta}(c_j^{\theta}) \quad (2.6)$$

Where c_j^{θ} is the averaged position of the maximum of the cross-correlation $Z_{ij}^{k,\theta}$, between the incoming unknown chirp S_i and the expected chirp S_j, over the number of channels K. The N energy values $\left\{Z_j^{k,\theta}\right\}_{k=1,\dots,K}$ are averaged over the number of channels K.

$$Z_j^{\theta} = \frac{1}{K}\sum_{k=1}^{K} Z_j^{k,\theta} \quad (2.7)$$

The frequency f_i^{θ} is selected with i such that:

$$Z_i^{\theta} = \max(Z_j^{\theta})_{j=1,\dots,N} \quad (2.8)$$

f_i^{θ} is assumed to be the carried frequency of the chirp among the N possible frequencies f_j^{θ} of the group θ. Thus, Θ frequencies f_i^{θ} are detected for each chirp. The succession of the bit sequences associated to each frequency f_i^{θ} gives the original bit sequence modulated by the chirp. Fig 2 gives an overview of the chirp demodulation for the maximum likelihood in the case of frequency hoped chirps.

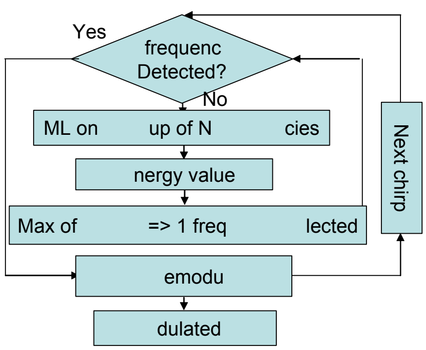

Fig. 2 Demodulation using the maximum likelihood technique

C- Channel Modeling

A model of the system is implemented using the work of Crepeau [11], and the passive sonar equation [6]. The Frame Error Ratio (FER) is a meaningful indicator of a communication system reliability [12]. The FER represents the number of messages non-decoded at the receiver. This ratio is a function of the bit rate, the medium properties, and the source level [10]. Crepeau [11] provides a model of the probability of bit error, P_b, for non-coherent MFSK modulation in a Nakagami-m acoustic channel, as shown in (2.9).

$$P_b = \frac{M}{2(M-1)}\sum_{i=1}^{M-1}\binom{M-1}{i}\frac{(-1)^{i+1}}{i+1} \times \left[\frac{m}{m+\frac{i}{i+1}\log_2(M)\frac{Eb}{N_0}}\right]^i \quad (2.9)$$

Where M is the type of M-ary FSK modulation used. m is the Nakagami-m channel parameter, computed with the signal amplitudes [11] obtained experimentally. Eb is the energy per bit and N_0 is the noise power per 1 Hz of frequency. The ratio Eb/N_0 is determined using field results.

To extend (2.9) to a coded sequence of bits the Bernouilli trials are used [9]. Bernouilli trials are experiments repeated n times with a certain event, in this case “one bit is wrong”, expected to occur k times. In the case of bit errors, the probability $p_n(k)$ of having k bit errors over a total number of n bits is given by the Bernouilli trial:

$$p_n(k) = \binom{n}{k} P_b^k q^{n-k} \quad (2.10)$$

Where

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \text{ and } q = 1 - P_b \quad (2.11)$$

Thus the probability of having zero bit errors over a sequence of n bits is:

$$p_n(0) = 1 - \sum_{k=1}^{n} p_n(k) \quad (2.12)$$

$p_n(0)$ represents the frame error probability, which leads directly to the frame error ratio.

III. SYSTEM CHARACTERISTICS

A- Message Structure

The message structure and the communication system are summarized Fig 3. The DPAM sends the same known series of $Q = 8$ chirps at the beginning of all its messages. Each of the 8 chirps carries a given frequency. If the incoming synchronization sequence carries at least 6 of 8 frequencies ($Q' = 6$) in the correct order, it is assumed that a coded message is coming. To identify which ECC and which hoping mode are used 2 chirps follow the synchronization chirps.

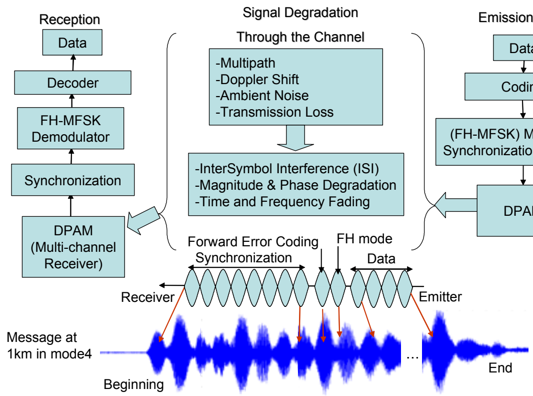

Fig. 3 Overview of the system

The first chirp carries one frequency among 3 possible frequencies ($N = 3$), corresponding to the 3 ECC techniques proposed. The second chirp carries one of the 4 different frequencies ($N = 4$) representing the 4 possible frequency hoping modes used. The carrier frequency of each chirp is estimated using the maximum likelihood (Fig 3).

B- Message Encoding

The DPAM is designed to transmit messages in multiple frames containing 256 bits of information. A 16 bit Cyclic Redundancy Check (CRC) code is added to the sequence [9]. The bit sequence is then coded using an ECC technique. In the case of Reed Solomon coding, the 272 bits are converted in a sequence of 384 bits [9] [7]. The convolutional coding converts the 272 bits sequence in a 588 bit sequence [9] [7]. The concatenated technique converts the original 272 bits in a 780 bit sequence [9] [7].

C- Modulation

Each chirp envelope is generated to a Blackman-Harris time window [9], used to reduce frequency leakage between chirps. Every chirp is sampled at 75600 Hz, lasts 13.54ms and occupies a bandwidth of 295.31 Hz. Up to 56 frequencies are used, of which 32 are reserved for data. There are 4 different transmission modes [9], corresponding to 4 different modulation techniques based on frequency hoping. Table 1 and Fig 4 summarize the different characteristics of the communication system for each frequency hoping mode.

TABLE 1 CHARCTERISTICS OF THE COMMUNICATION SYSTEM AS A FUNCTION OF THE FREQUENCY HOPING MODE USED

FH mode	Number of hops	Frequencies /chirp (Θ)	Frequencies /group (N)	Bits/ chirp	Speed (cps)
4	4	1	8	3	221
3	2	2	8	6	442
2	0	4	8	12	879
1	0	8	4	16	1172

TABLE 2 SPEEDS OF TRANSMISSION IN BIT PER SECOND AS A FUNCTION OF THE FREQUENCY HOPING MODE AND THE ECC

ECC	FH mode	bps	ECC	FH mode	bps	ECC	FH mode	bps
Reed Solomon	4	148	Viterbi	4	97	Reed Solomon /Viterbi	4	73
	3	295		3	193		3	145
	2	591		2	385		2	291
	1	788		1	510		1	386

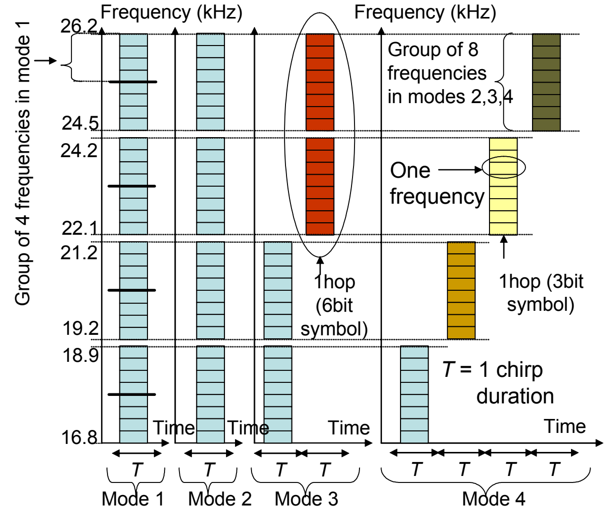

Fig. 4 Frequency groups used to demodulate a chirp for each frequency hoping mode

In mode 4, each chirp represents 3 coded bits, and uses one ($\Theta = 1$) out of 8 ($N = 2^3$) frequencies. Since that 32 frequencies are used for data modulation, 4 hoping groups of 8 frequencies can be used sequentially. This reduces considerably the negative impact of time and frequency-selective fading. This mode is the slowest mode at 221 coded bits per second (cps), but it is also the most robust.

In mode 3, 2 frequencies ($\Theta = 2$) are sent per chirp. Each of the 2 frequencies belongs to a separate hoping group. Thus, 6 bits are sent per chirp. 2 groups of 8 frequencies ($N = 8$) are needed to modulate a chirp. Since this mode uses 2 frequency hops, it is less robust than the mode 4. However the speeds of transmission are 442 cps.

In mode 2, one frequency of each group is used per chirp ($N = 8$) so 4 frequencies are sent ($\Theta = 4$) encoding 12 bits. Since all 4 groups are used to modulate one chirp, this mode does not use frequency hoping and is more sensitive. The speeds of transmission are 879 cps.

In mode 1, a frequency encodes 2 bits. Thus to encodes all the possible 2 bits sequences it is needed to use 2^2 or 4 frequencies ($N = 4$). Eight groups ($\Theta = 8$) of 4 frequencies are used to modulate a chirp containing 16 bits of data. This mode does not used frequency hoping. It is the fastest mode with speeds of 1172 cps.

IV. MODEM TESTING

A- Channel Characteristics

Two modems were tested North East Port Everglades, Florida, in a water column of 60 ft. Each modem was setup on a boat and placed at distances of 1, 2, and 3 km apart (Fig 5).

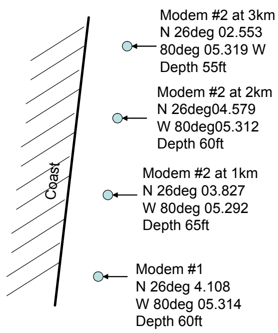

Fig. 5 Locations of the 2 acoustics modems

The noise Power Spectral Density (PSD) function is presented in Fig 6.

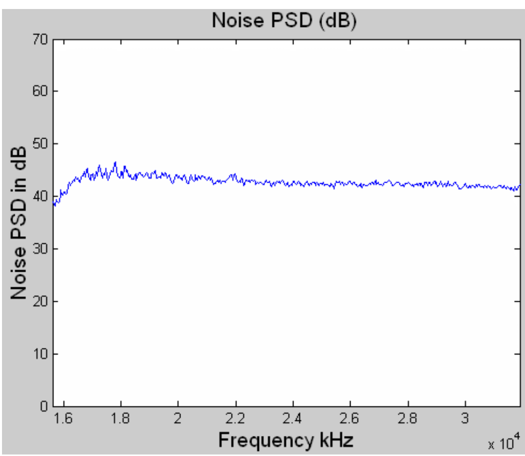

Fig. 6 Noise Power Spectral Density function

Note that the ambient noise, assumed to be Additive White Gaussian Noise (AWGN) in the model of Crepeau, is in reality a colored noise.

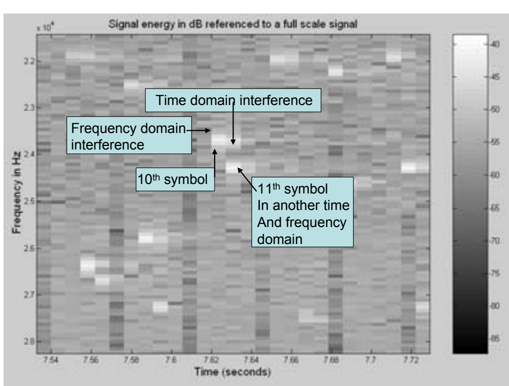

Fig.7 Spectrum of a signal at 1 km

Fig 7 shows the amount of time and Doppler spread at 1 km. The reverberation time is estimated at 3 chirps at 1 km, and 2 chirps at 2 and 3 km. The reverberation time does not exceed 3 chirps duration, which means that in frequency hoping mode 4, the signal is not affected by reverberation.

Fig 8 presents the sound speed profile as a function of the depth. The plot shows a variation of the order of 1 ms^{-1} of the sound velocity as a function of the depth. This means that the channel is isospeed, typical of a shallow water environment.

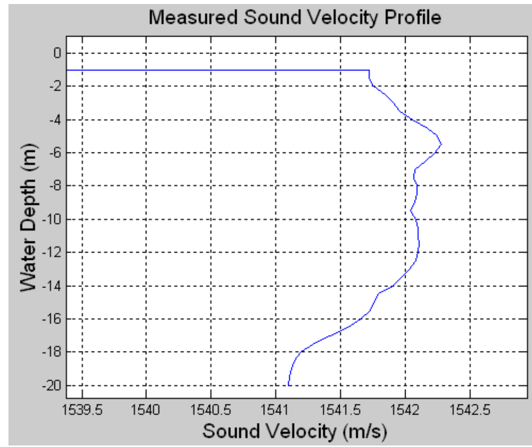

Fig.8 Sound speed profile as a function of the depth

B- Test Results

At each distance the performance of the modems were tested using all the frequency hoping modes and ECC techniques.

TABLE 3 PERFORMANCE AT SEA OF THE DPAM USING 4 CHANNELS

Mode	ECC	% of received messages		
		1km	2km	3km
4	Concatenated	100	80	100
4	Viterbi	100	60	50
4	Reed Solomon	100	100	60
3	Concatenated	100	80	50
3	Viterbi	100	90	90
3	Reed Solomon	90	80	50
2	Concatenated	40	20	0
2	Viterbi	40	0	0
2	Reed Solomon	0	0	0
1	Concatenated	50	0	0
1	Viterbi	60	0	0
1	Reed Solomon	20	0	0

Table 3 summarizes the performance obtained for the modem, using 4 channels. The percentages represented are the percentages of messages received over a set of 10 messages. The most sensitive modes 1 and 2 cannot be detected at 2 and 3 km. While the modes 3 and 4, using frequency hoping, can be received at distances up to 3 km. The concatenated mode outperforms the Viterbi which outperforms the Reed Solomon technique.

TABLE 4 PERFORMANCE OF THE DPAM WITH 4 CHANNELS USING THE MODEL OF CREPEAU

Mode	ECC	% of received messages		
		1km (m = 1.3)	2km (m = 1.5)	3km (m = 0.9)
4	Concatena	100	100	98
4	Viterbi	100	100	97
4	Reed Solo	100	100	96
3	Concatena	100	99	83
3	Viterbi	100	98	80
3	Reed Solo	100	96	78
2	Concatena	92	68	46
2	Viterbi	80	66	41
2	Reed Solo	83	65	39
1	Concatena	71	55	31
1	Viterbi	77	51	29
1	Reed Solo	68	48	23

Data, in the 4 different frequency hoping modes, coded using each ECC technique, have been recorded at each distance. Such field results allow the computation of the parameters *m* and *Eb* of the model of Crepeau. Also, Fig 6 gives the value of N_0. Table 4 presents the performance of the system evaluated for 4 channels using the model of Crepeau. The experimental results, obtained over 10 messages only, fairly match the predictions of the model, estimated over 1000 messages. The model tends to overestimate the performance of the communication system. Indeed, it is assumed that the source and the receiver are fixed and omnidirectional, and that the noise is AWGN. However, the ocean ambient noise is closer to a colored noise (Fig 6), and the source and receiver have relative motion. Such assumptions set a lower bound to the error estimation. At a long range (3 km), the FER is high and the model approximations do not significantly impact on the results. At short range (1 to 2 km), where the FER is small, the results are more sensitive to the error added by the assumptions, causing the model to underestimate the FER at short range.

V. CONCLUSION

A new demodulation technique for FH-MFSK communications has been developed at Florida Atlantic University. The demodulator uses a synchronization method based on the correlation of the signal with a known sequence of chirps. The demodulation is made using a multichannel Maximum Likelihood technique. The frequency assumed to be carried by the signal is the one corresponding to the maximum of energy. Such a non coherent demodulation technique has been implemented for the 4 channel DPAM. Experimental results have shown that the modem is able to decode messages at 221 cps and 442 cps at 3 km. While at 2 km messages at 442 cps can reliably be received. At 1 km messages transmitted at all speeds are successfully received. The recording of signals at 1, 2 and 3 km allow a simulation of the acoustic channel using the model of Crepeau. The results of such a model match the field results fairly.

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