On joint acoustic communication and positioning through MFSK-modulated signals and Costas arrays

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Abstract-**The underwater positioning applications with ultra-short base line (USBL) antenna have expanded significantly over last decades. Their principles are based on the geographical positioning of transponders emitting deterministic waveform such as Costas arrays from a receiving antenna composed of several acoustic transducers. Recovering from the transponder of external information such as immersion can increase accuracy of USBL positioning system. Jointly achieving a digital positioning and communication in a shallow water channel requires a careful design of the algorithms to get acceptable performance at limited complexity. This issue is investigated in the present paper. A processing chain design combining underwater acoustic communication and positioning through BFSK modulation of the data over Costas arrays is proposed, discussed and evaluated. Results show that the developed communication method is an efficient tradeoff between simultaneous transmission of telemetry data and positioning signal at a limited complexity. An experiment at sea will be conducted by IXSEA soon to confirm these first lab results.**

I. INTRODUCTION

USBL antenna [1] [2] detects and locates transponders which are mounted on autonomous underwater vehicles (AUV) or scientific mooring by their acoustic signature. The underwater acoustic channel is characterized by a short available bandwidth due to loss of transmission increasing with both range and frequency. Within this bandwidth, the acoustic signals are subject to noise and time-varying multipath. Severity of this environment especially in shallow water conditions added to the multiple access objectives requires robust waveforms. Costas arrays satisfy this constraint and are commonly used in USBL applications. In the same time, increasing of positioning accuracy needs the use of other information such as transponder immersion, which can be deduced from pressure sensor measure could be transmitted across acoustic channel to the positioning antenna. In conventional data transmission scheme, the information is structured in frames composed of a deterministic preamble and the data broadcasted. The preamble allows identification of the beginning of the frame and initialization of the equalizer to compensate channel impulse response. This scheme increases signal duration and reduces the autonomy of transponder which operates on battery. In the same time, beacons have small processing capabilities to minimize consumption. Consequently, the delivery of the collected telemetry requires short and infrequent emission based on a simple embedded architecture. Therefore, joint acoustic positioning and communication should minimize consumption of underwater deployed systems.

This paper is organized as follows. In section II, we present principles of a joint positioning and communication transmitter. Then, in third section, we present the acquisition process and the receiver structure. System performances are illustrated in section IV. Finally, section V will draw some concluding remarks.

II. TRANSMITTER DESIGN

In this section, we focus on the transmitter design which combines Costas sequences for positioning, Barker code for redundancy, and telemetry data.

A. *Costas Arrays*

Costas waveforms [3] are sequences, or pulse trains, of short subpulses of continuous-waves of distinct frequencies, based on frequency hopping. Frequency-hopped signals consist of a waveform of total duration T, subdivided into N subpulses of duration $\{t_1,t_2,\ldots,t_N\}$, during which a frequency chosen from a set of N available different frequencies $\{f_1,f_2,\ldots,f_N\}$ is transmitted. Fig. 1 illustrates the instantaneous frequency of the resulting signal, which is described by a Costas sequence $\{\theta_n\}$.

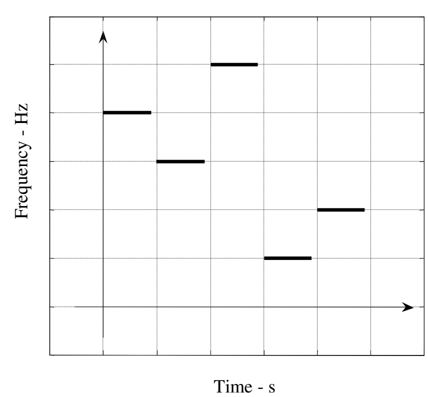

Figure 1. Time frequency structure of
5 elements Costas array

TABLE I
COSTAS 16-ARRAYS (P = 17, N = 16)

Code No.	Sequence $\{\theta_n\}$							
1	1	3	7	12	11	14	8	6
	16	9	15	4	13	5	2	10
2	3	12	10	4	16	5	7	8
	15	1	14	13	9	2	6	11
3	5	7	13	2	6	9	16	12
	10	4	14	1	15	3	11	8

A Costas sequence has the property that differences θ_{n+i} - θ_n are unique for all n for any lag i [4] where i represents the order of the difference. One method that can be used to generate Costas sequence is the Welch-Costas method [5]. This method takes a primitive root [6] g of a prime number p and generates a sequence from the $p-1$ successive powers of g modulo p, i.e., the sequence $g^n \ mod \ p$, for $n = 1,\ldots,p-1$. Using a prime of p = 17, Table I lists the three Costas sequences or « Costas arrays » thus generated.

Using a center frequency f_0 and a bandwidth B_{Costas}, each element θ_n from a Costas code in Table I can be used to generate a subpulse frequency by using

$$f_n = \left(f_0 - \frac{B_{Costas}}{2} \right) + (\theta_n - 1)\frac{B_{Costas}}{(N-1)} \tag{1}$$

where f_n is the calculated frequency of the subpulse.

The complex representation of the Costas pulse train s(t) can be given by [3]

$$s(t) = \sum_{n=0}^{N-1} p_n(t - nT_S) \tag{2}$$

where

$$p_n(t) = \begin{cases} e^{j 2\pi f_n t} & \text{for } 0 \le t \le T_S \\ 0, & \text{elsewhere} \end{cases} \tag{3}$$

where p_n is the subpulse, T_s is the subpulse period given by T/N, and f_n is the subpulse frequency given by (1). In addition to allowing the signal identification, the arrangement facilitates the receiver synchronization.

B. Redundancy

To ensure telemetry transmission, redundancy is added to the binary data by using a Barker code [7], which is a sequence of K value $a_i \in \{-1, +1\}$; $i=1,\ldots,K$ such as

$$\left| \sum_{i=1}^{K-v} a_i a_{i+v} \right| \le 1 \quad \text{for all } 1 \le v < K \tag{4}$$

Each data bit to transmit is substituted by the Barker code according to the sign of the binary data.

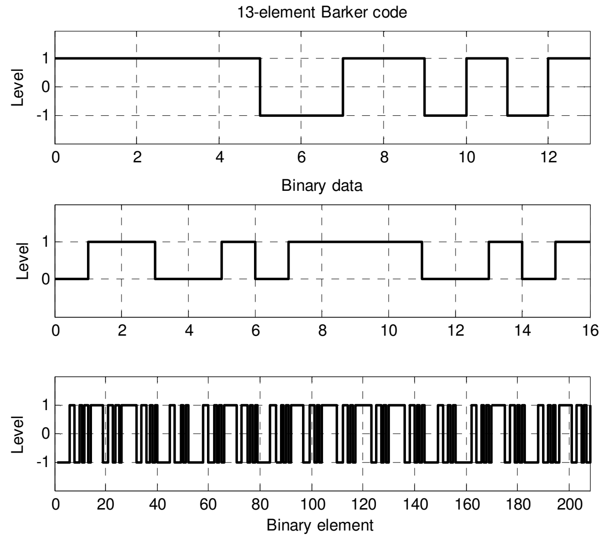

Figure 2. Example of combination of Barker code with binary data

Typically, for a Barker code of length $K = 3$, state '1' of binary data is associated to the sequence {+1, +1, –1} while the state '0' is linked to {–1, –1, +1}. Fig. 2 illustrates the association between the sequences of Barker of length $K = 13$ and telemetry information. Barker sequences have been chosen as redundancy code here due to the low peak-to-peak sidelobe ratio characteristics that allow recovery of transmitted information. Minimum Peak Sidelobe Code or Nested Codes [7] can be cited as alternate solutions. Then the resulting bit stream is the input of the modulator which relies on Costas sequences.

C. Modulation structure

The binary sequence is then converted into symbols by a Binary Frequency Shift Keying (BFSK) modulator. In a baseband model of the BFSK scheme the transmitted signal during time slot τ is

$$q(t) = \begin{cases} q_{-1}(t) = e^{-j\pi B_M t} \\ q_1(t) = e^{j\pi B_M t} \end{cases} \quad \text{for } 0 \le t \le \tau \tag{5}$$

where B_M corresponds to the bandwidth of FSK modulation with $\tau = 1/B_M$.

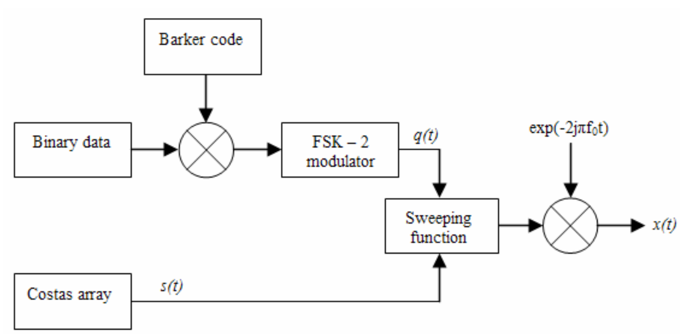

Figure 3. Transmitter structure

The transmitter illustrated on Fig. 3 consists of the modulation by a sweeping function [8] of BFSK symbols *q(t)* with Costas waveform *s(t)*. The immersion information obtained from the pressure measured by the beacon is coded on *R* bits, such that the following constraint is satisfied:

$$R = \frac{T}{(K\ \tau)} \tag{6}$$

where *R* is a non zero natural number, *T* represents duration of the Costas array, *K* is the number of elements of redundancy code and τ the BFSK duration. In our study, we consider $R = N$; each of *N* Costas array subpulse is associated to a Barker sequence which codes a binary element *R*. Subsequently, resulting waveform *x(t)* is amplified, and emitted by the transducers across the underwater acoustic channel. With this method, Costas array becomes the vector of transmission of the telemetry information.

III. Receiver design

In this section, we focus on the demodulator design for joint acoustic communication and positioning. After reception on the hydrophone, acoustic observation is filtered, amplified, digitized and transposed to baseband.

A. Receiver preprocessing

The aim of the preprocessing step is to identify if the observation contains information tracked and when this waveform arrived on the hydrophones. Preprocessing block consists of *X* parallel matched filters, where *X* is the number of transponder used by positioning application.

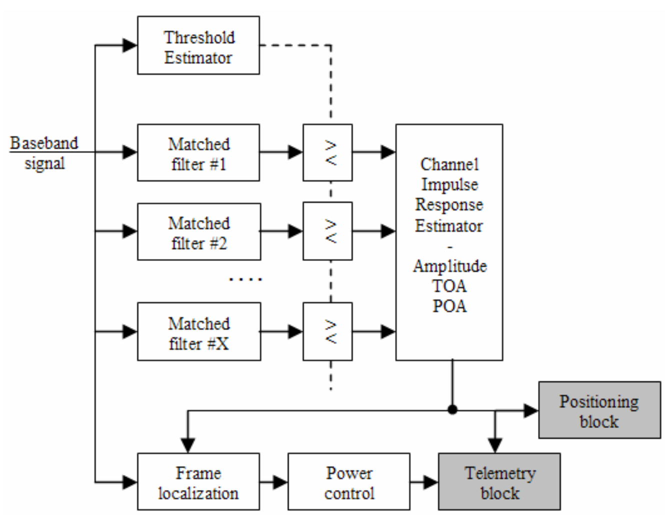

Figure 4. Preprocessing stage

Fig. 4 illustrates the preprocessing block operations which permit positioning the beacon and recovery of the telemetry data. BFSK modulation of telemetry data on Costas array disrupts correlation process due to the mismatch between the transmit signal and the theoretical Costas code used at the receiver. Indeed, to overcome lack of information on the binary stream, it is necessary for each Costas array to sum two matched filter. The first matched filter corresponds to a binary sequence which contains exclusively the state *'1'* and another which is associated to bits *'0'*. Analytically, the summation of two outputs can be summarized as follow to define optimal waveform used for pulse compression.

$$m(t) = s(t) * \left(\exp\left(2\, j\, \pi \frac{B_S}{2} t \right) + \exp\left(-2\, j\, \pi \frac{B_S}{2} t \right) \right) \tag{7}$$

where *m(t)* denotes waveform used by the receiver, *s(t)* is the Costas array. After simplification of the Euler's formula, we get the following waveform at the receiver:

$$m(t) = 2 * \cos(\pi\, B_S\, t) * s(t) \tag{8}$$

This new waveform ensures detection of Costas signal transmitted regardless of binary data conveyed. In the same time, an automatic threshold, based on constant false alarm rate (CFAR) design, is estimated. The outputs of matched filters are compared to the threshold to identify if observation contains useful data and which transponder has sent it.

All detections exceeding threshold are identified by the Channel Impulse Response Estimator (CIRE) which aims to collect data such as amplitude of the signal, time of arrival (TOA) and phase of arrival (POA). These data are then used to determine the positioning of the beacon but also to initialize the filter structure used for the equalization of telemetry data.

Positioning block exploits TOA and POA of the waveform on each hydrophone of the antenna structure to estimate the precise delay between hydrophones. According to antenna structure, inertial data and sound velocity, USBL algorithm [2] locates transponder position.

B. Telemetry block

Frame localized whose synchronization has been achieved by the pulse compression process of the preprocessing step is equalized thanks to information provided by the CIRE block. In addition to the equalizer, data recover requires suppression of Costas array identifier, BFSK demodulation and a matched filter with redundancy sequence.

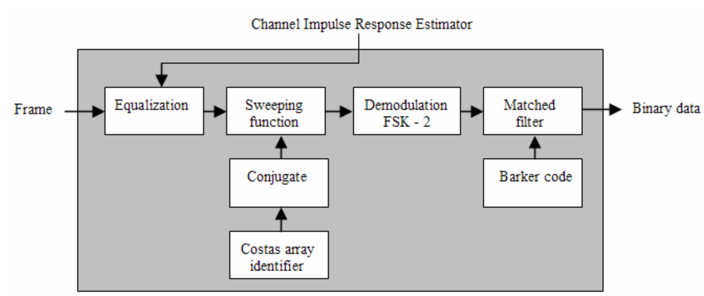

Figure 5. Telemetry block

Fig. 5 presents the structure of telemetry block composed of an equalizer, a suppression of Costas array, a BFSK demodulator and a matched filter to recover data. The first step of this stage, devoted to equalization process, is not investigated in the present paper. Many procedures are discussed in the literature [9] to reduce the channel impact. Channel profile provided by CIRE will help to reduce disruption due to channel. In addition to the equalizer, removing of the Costas code reduces the impact of multipath on the received signal. Indeed, the demodulation of the detection pattern is the principle introduced by Zielinski and Barbour in [8] through use of sweeping functions in presence of multipath. Use of Costas codes instead of the traditional linear frequency modulation reduces the efficiency of this method but allows use of multiple waveforms simultaneously with a relative orthogonality. Then, resulting signal is demodulated with a conventional FSK method to recover binary elements. Redundancy given by Barker code is suppressed by matching binary stream with reference sequence.

IV. NUMERICAL RESULTS

A. *Shallow water acoustic channel model*

To evaluate performances of our transmission chain, numerical simulations have been conducted. The transmission is achieved through use of channel models obtained during trials at bay of Morgat (48°11'00" North; 4°26'00" West) near Brest in France. The transmission is performed for a distance of 3 km, with a transmitter placed on the seabed to a depth of 25 meters and an antenna immerged at 3 meters. For this propagation condition in very shallow water, several measures of channel impulse responses were recorded to develop our USBL applications named Global Acoustic Positioning System (GAPS).

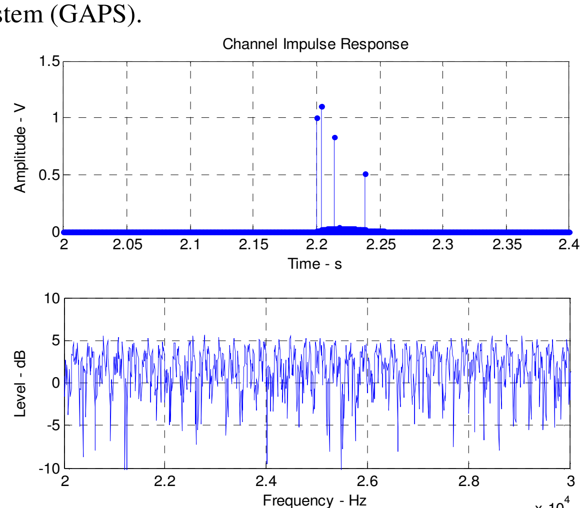

Figure 6. Channel impulse response and Channel frequency response

The averaged impulse response and frequency response, shown in Fig. 6 is used as part of our implementation to evaluate performances of the transmission chain.

Channel impulse response is composed of 4 main paths. The two main paths are separated by a few milliseconds; the second path has higher level than the direct path.

B. *Signal transmission*

Simulated signal has duration (T) of 0.05 s and a bandwidth (B) of 9280 Hz centered on 25000 Hz. On the total bandwidth, 4160 Hz is allocated to the transmission of data (B_M) and 5120 Hz is exploited by the code of Costas (B_{Costas}). Costas signals have a processing gain BT expressed in dB given by the product of the signal duration with its bandwidth is 24 dB.

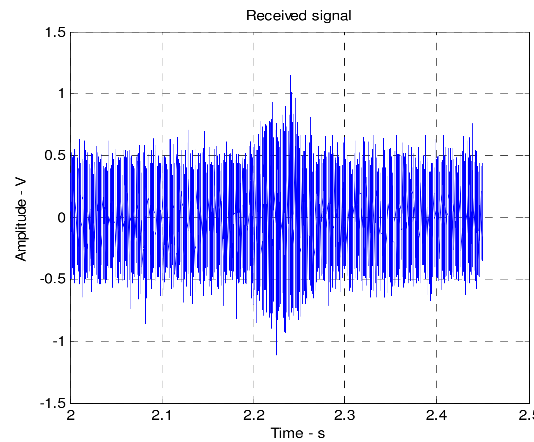

Figure 7. Received signal

Fig. 7 illustrates the receiving of an amplified and filtered signal on a hydrophone of the positioning antenna for 5 dB of signal to noise ratio (SNR). Then, this observation is utilized by the preprocessing block.

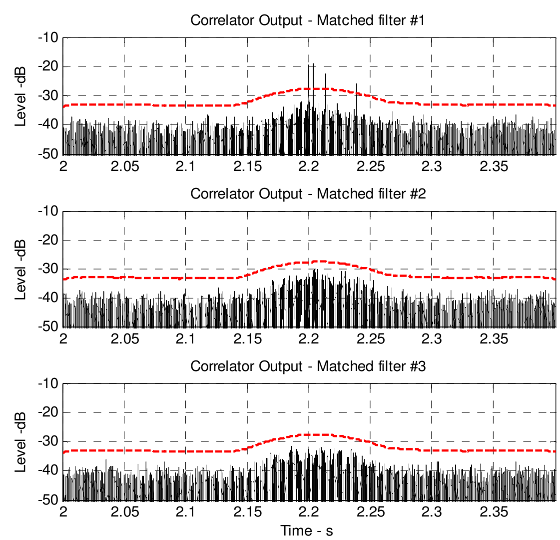

Figure 8. Output of preprocessing block and the estimated threshold (dashed line)

Outputs of matched filters are compared to the threshold (dashed line) to determine which transponder sent its identifier. This principle is shown on Fig. 8 and permits to disclose low correlation properties of Costas array even if these sequences contain telemetry data.

C. *Receiver performance*

The transmission performance is evaluated through benchmark tests with 10000 iterations in each run for various inputs SNR. Performance on the multipath channel is compared to that of an ideal channel in the presence of AWGN; a pure BFSK modulation is also considered.

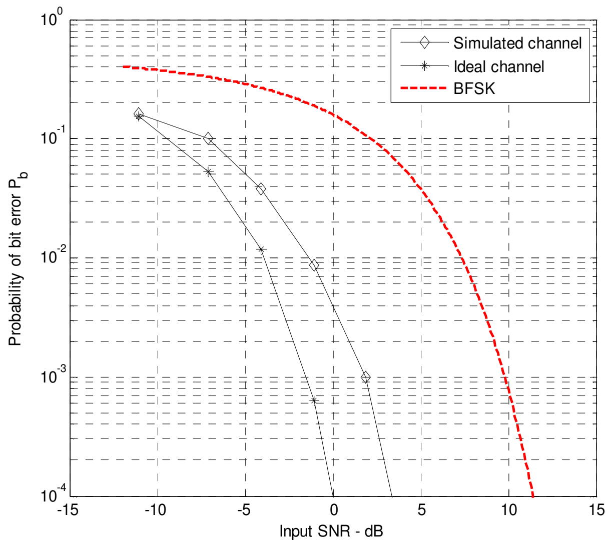

Figure 9. Performance of processing chain

Fig. 9 shows benefit of redundancy sequence which translates BFSK performances to low signal to noise ratio. Indeed, processing gain gives by Barker code expressed in dB is linked to the length of this sequence. In our study, the 13 elements of Barker codes produce a processing gain of 11 dB. Consequently, for an ideal channel or an equalized channel, we can obtain a bit error rate (BER) around 10^{-2} for an input SNR less than 0 dB. Thereby, for each pulse emitted by a transponder, 16 elements are sent to the positioning antenna during 50 milliseconds. These characteristics correspond to a bit rate of 320 bits per second.

V. CONCLUSIONS & FUTURE WORK

Motivated by performance improvements of USBL systems using immersion of the transponders, we have examined the feasibility of joint acoustic communication and positioning. We have adopted the use of BFSK modulation to add telemetry information on Costas codes used in positioning application. The proposed scheme, which yields encouraging results, can still be enhanced.

The future work should focus on channel equalization and on the use of antenna diversity by considering a single input multiple output (SIMO) approach. These two ways of improvements are currently under investigation. Finally, to confirm these first results, an experiment at pool or at sea will be performed soon.

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