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Experimental validation of a chirp-based underwater acoustic communication method

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A wireless underwater acoustic communication algorithm based on the combination of chirp modulation and direct-sequence spread-spectrum signalling is presented. In this paper, the processing chain design is proposed, discussed, and demonstrated using real data. The communication algorithm is made of a transmission block encoding the bits with adequate linear chirps multiplied by pseudo noise (PN) sequences, and a rake receiver that allows one to positively exploit the energy present in the most significant propagation paths. The use of chirp signals takes advantage of the low Doppler sensitivity in the matched filter operation whereas the choice of PN sequences allows one to reduce narrowband interference arising from other users and self-interference due to multipath propagation. Moreover a tracking procedure that allows an adaptation to the instantaneous Doppler shift has been devised and tested. Some experiments have been carried out changing the distance and the speed between transmitter and receiver. Results show that the developed communication method is able to handle the multipath phenomenon and the Doppler effect, allowing one to achieve a bit error rate less than 10^{-3} for long ranges for bit rates of about 15 and 230 bit/s.

1 Introduction

An underwater acoustic channel is characterized by a limited available bandwidth due to the transmission loss increasing with both range and frequency. Within this bandwidth the acoustic signals are subject to time-varying multipath which may result in inter-symbol interference and large Doppler shifts and spreads, especially in shallow water channels [1]. In this work the experimental validation of a wireless underwater acoustic communication system based on the combination of chirp modulation [2]-[10] and direct-sequence spread-spectrum signaling is presented [2],[6],[9]. The use of chirp signals takes advantage of the low Doppler sensitivity in the matched filter operation [2]-[4] whereas the choice of pseudo noise (PN) sequences allows one to reduce narrowband interference arising from other users and self-interference due to multipath propagation [11],[12]. Moreover one of the most important advantage of a direct sequence spread spectrum approach is privacy that can be achieved through the use of pseudo random noise. The system here described is made of a transmitter encoding the bits with linear chirps multiplied by PN sequences, and a rake receiver that allows one to positively exploit the energy present in the most significant propagation paths [13]. Moreover a tracking procedure that allows an adaptation to the instantaneous Doppler shift has been devised and tested. Results, obtained on real data over a long-range shallow-water channel with a moving transmitting platform, are presented and discussed.

2 The communication algorithm

The system here presented consists in the combination of chirp modulation with a direct sequence spread spectrum approach. This integration allows one to enhance the communication system performances [2].

2.1 The Transmitter

The transmitter is composed of a binary source, an encoder and a PN code generator. A PN code is a sequence of values '1' and '-1'; each value is called chip. The frequency of the chirp signal can vary linearly increasing from a frequency, f_0 , to a higher frequency, f_1 . We shall call such signal Up-Chirp. The chirp signal that

varies its frequency in the opposite way will be called Down-Chirp.

The transmitter encodes the bits coming from the source assigning an Up-Chirp to the '1' value and a Down-Chirp to the '0' value, occupying in both cases the same bandwidth and same duration.

A sequence of chirp signals (encoding the binary data) is then multiplied by a period of a PN code. If we denote with I_k the k -th bit of the data sequence, with $k=0:N-1$, T the bit duration, L the length of the PN sequence, T_c the chip duration, $M = NT/LT_c$, then the modulated signal sent through the channel is $m(t)$:

$$m(t) = \sum_{k=0}^{N-1} ch_k(t - kT) \cdot \sum_{i=0}^{M-1} p(t - iT_cL) \quad 0 < t < NT$$

$$p(t) = \sum_{n=0}^{L-1} p(n)q(t - nT_c) \quad (1)$$

$$ch_k(t) = \cos \left(2\pi \left((2I_k - 1) \left(\frac{f_1 - f_0}{2T} \right) t^2 + ((1 - I_k)(f_1 - f_0) + f_0)t \right) \right)$$

where $q(t)$ is a unitary pulse of duration T_c and $p(n)$ is the PN sequence (with values '1' and '-1') of length L .

Figure 1 shows an example of PN chirp coding where a chirp signal corresponding to one bit is multiplied by a PN sequence period.

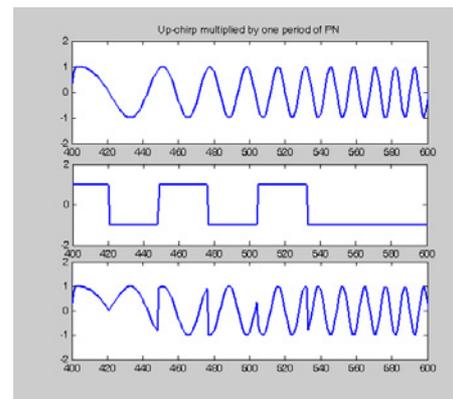


Fig. 1. Example of combination of chirp modulation with direct sequence approach.

A kind of PN code that possesses properties ensuring both favourable auto- and cross-correlation characteristics is the Gold code.

A Gold code can be generated by performing an XOR operation between two m-sequences (maximal length sequences) of the same length. In order to obtain m-

sequences of length 2^n-1 a Linear Feedback Shift Register composed of n taps can be employed [11].

2.2 The Receiver

In relation to the strong multipath present in a shallow water channel and to the adopted modulation (direct sequence spread spectrum with chirp) a reasonable choice to decode the received data is given by the use of a rake receiver [13]. In addition to suppressing the inter-symbol interference, a rake structure can be employed to make use of the energy present in multiple propagation paths. The rake receiver is a matched filter that uses a tap delay line to combine signals arriving over multipath propagation. Signals at the taps are first multiplied by the corresponding PN sequences. The output of the matched filter of each rake tap is compared with a threshold. At the end of all the taps a counter (called multipath counter) records how many multipath components are enough energetic. The receiver here proposed is composed of two different modules: one corresponding to the Up-Chirp, the other to the Down-Chirp.

The final decision is made comparing for each bit the output of the Up-Chirp module with the one of the Down-Chirp module. Such vectors allow one to evaluate for each transmitted bit the number of propagation paths over the chosen threshold (the most energetic paths).

Due to the motion of the transmitting and receiving platforms, during the reception of long sequences of bits, the change of the instantaneous sampling frequency produces an extension or a reduction of the received samples sequence leading to problems of synchronization for every bit of the message. To compensate this effect a tracking of the Doppler frequency has been devised. The received signal is subdivided into blocks of Z bits (see Fig. 2). For every block the rake receiver provides the bits estimation and in the meanwhile the information about which tap supplies the most energetic contribution is stored. The Doppler compensation is achieved imposing that two sequential blocks have the maximum matched filter output for the same tap according to the following steps. Each block passes through the rake receiver.

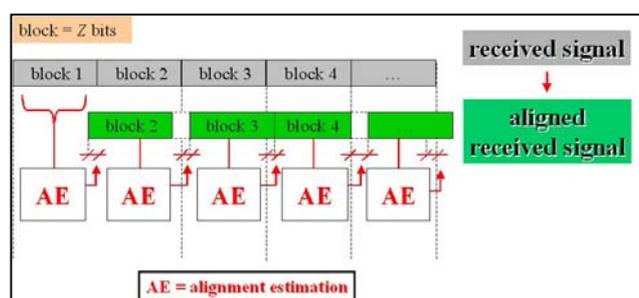


Fig. 2. Doppler compensation scheme.

While the Z bits are processed by the rake receiver, the Doppler tracking procedure performs the following operations:

- For each tap computation of the mean value of maxima of matched filter output for the Z bits.
- Selection of the tap corresponding to the maximum mean value.

- Comparison of the delay time of the selected tap with the one obtained for the previous block.
- Computation of the alignment on the basis of such comparison.

3 Synchronization

For the registration of the signal portion to be analyzed by the receiver, a preamble is placed at the beginning of the message. At the receiver, a filtering operation matched to the chosen and known preamble allows one to find the time instant to start the acquisition of the information signal. Two different preambles have been used: the first one is a pattern of k bit, modulated in the same way of the information bit; the second one is a chirp signal with a duration of 1 second. The pattern of k bit satisfies the requirement of covertness but it is more difficult to detect, whereas the 1-second chirp is more visible to the receiver but also to an unintended listener.

4 Results

The underwater acoustic communication chain has been validated on real data collected in the Baltic sea and in the North sea. In particular, data at a rate of 13 bit/s and 226 bit/s, over long ranges and with a transmitting platform moving up to 3 m/s, have been taken into account.

4.1 13 b/s data rate results

The underwater acoustic communication system has been validated on real data collected in the Baltic and North sea.

In particular, the parameters common to all the runs are:

- Source: 13 b/s
- Total available bandwidth: 3.5 kHz ($(f_c-1.75 \text{ kHz}) \div (f_c+1.75 \text{ kHz})$ with f_c carrier frequency).
- Each chirp is multiplied by one period of a Gold sequence made of 63 chips.
- Chirp bandwidth: 1.7 kHz ($(f_c-0.85 \text{ kHz}) \div (f_c+0.85 \text{ kHz})$)
- Sequence: 384 bit.
- Block size for the Doppler tracking procedure: 5 bits.

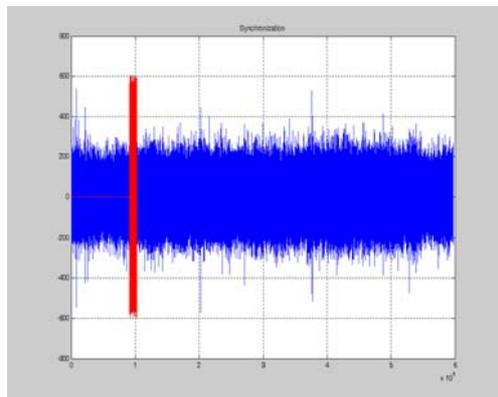
The synchronization preamble is made of a pattern of 10 bit modulated in the same way of the message for the Baltic Sea experiment, whereas a chirp signal with bandwidth equal to 3.5 kHz ($(f_c-1.75 \text{ kHz}) \div (f_c+1.75 \text{ kHz})$ with f_c carrier frequency) and duration equal to 1 s has been used for the North Sea trial.

Different experiments have been carried out changing the distance and the speed between transmitter and receiver. Two transmitters have been used with different carrier frequencies: 3.3 kHz and 5 kHz. The receiver is a vertical array made of 8 hydrophones ($10 \div 90 \text{ m}$).

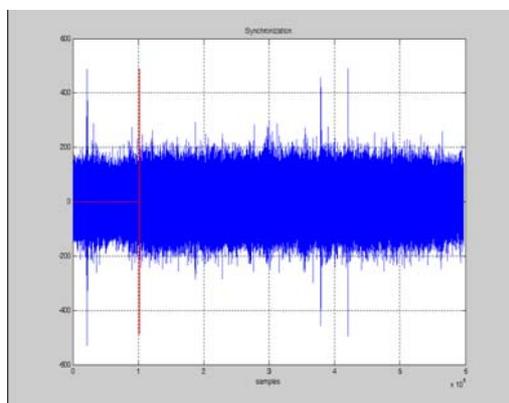
After the synchronization procedure, the signal received by one of the sensors is processed by the Rake receiver.

In Fig. 3 two examples of synchronization with different preambles are shown. The upper panel is relative to a pattern made of 10 bits = [0 0 1 0 0 0 1 1 0 0] (Baltic Sea).

The distance between the transmitter and receiver is equal to 7.5 km. The pattern is presented in red color overlapped to the corresponding sequence in the received signal. In the lower panel the synchronization is performed using a chirp signal of 1-s duration (North Sea). The distance between the transmitter and receiver is equal to 30 km. The red line shows the start of the information message.



(a)



(b)

Fig. 3. Data rate 13 b/s: synchronization result for different preambles: (a) pattern of 10 bits; (b) 1-s chirp signal.

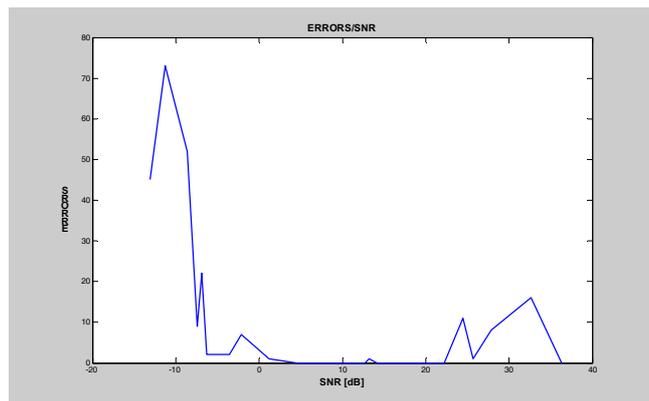


Fig. 4. Data rate 13 b/s: Graphic showing the number of errors/ping committed at different SNR. Distance between Tx and Rx from 2km to 37 km. Speed: 3 m/s.

Several runs with different working conditions have been analyzed; in Fig 4 we present a graphics describing the number of errors/ping committed for a specific run characterized by the following parameters:

- North Sea;
- Receiving channel depth: 90 m;
- 384 bit/ping

- Scenario: outbound
- Range: from 2 km to 37 km
- $f_c = 5$ kHz

In TABLE I results about some experiments with varying distance, speed and SNR are presented. Each row is related to the transmission of one ping containing 384 information bits.

Tx-Rx [km]	Speed [m/s]	SNR [dB]	Errors
7.5	0	3.8	0
7.5	0	-4.9	0
7.5	0	-9.2	4
7.5	0	-12.1	217
18.5	3	1.8	0
17.5	3	5.8	0
17	3	-6.1	2
27	3	-2.1	7
37	3	-13.1	45
52	0	0.6	0
52	0	-1.9	1
52	0	-4.3	13

TABLE I. Errors related to different working conditions (13 b/s)

4.2 226 b/s data rate results

The underwater acoustic communication algorithm has been validated also for a higher bit rate on real data collected in the Baltic and North sea.

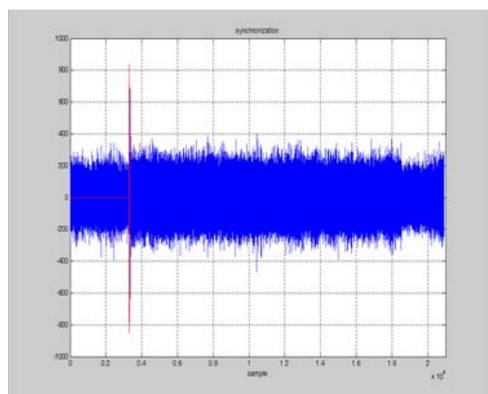
In particular, the parameters common to all the runs are

- Source: 226 bit/s
- Total available bandwidth: 3.5 kHz ($(f_c - 1.75 \text{ kHz}) \div (f_c + 1.75 \text{ kHz})$ with f_c carrier frequency).
- 51 chirp-bit are multiplied by one period of a Gold sequence made of 255 chips.
- Chirp bandwidth: 1.7 kHz ($(f_c - 0.85 \text{ kHz}) \div (f_c + 0.85 \text{ kHz})$)
- Sequence: 5760 bit.
- Block size for the Doppler tracking procedure: 51 bits
- $f_c = 3.3$ kHz

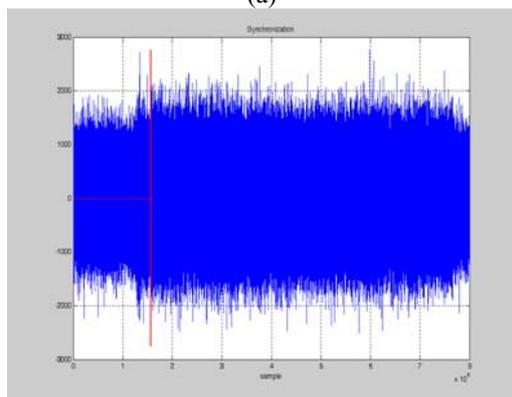
Again two different preambles have been used for the synchronization task: pattern of 10 bit for the Baltic Sea and the chirp signal with the duration of 1 s for the North Sea runs.

After the synchronization procedure, the signal received by one of the sensors is processed by the Rake receiver.

In Fig. 5 two examples of synchronization with different preambles have been shown. The pattern of the upper panel is made of 10 bits = [0 0 1 0 0 0 1 1 0 0]. The distance between the transmitter and receiver is equal to 7.5 km. For the lower panel the pattern is made of a chirp signal with duration equal to 1 s. The distance between the transmitter and receiver is equal to 15 km. The synchronization instant is shown with a red line for both panels.



(a)



(b)

Fig. 5. Data rate 226 b/s: synchronization result for different preambles: (a) pattern of 10 bits; (b) 1-s chirp signal.

In Fig. 6 we present the graphic describing the number of errors/ping committed for a specific run with the following working condition:

- Baltic Sea
- Receiving channel depth: 50 m;
- 5760 bit/ping
- Scenario: stationary
- Range: 7.5 km
- $f_c = 3.3$ kHz.

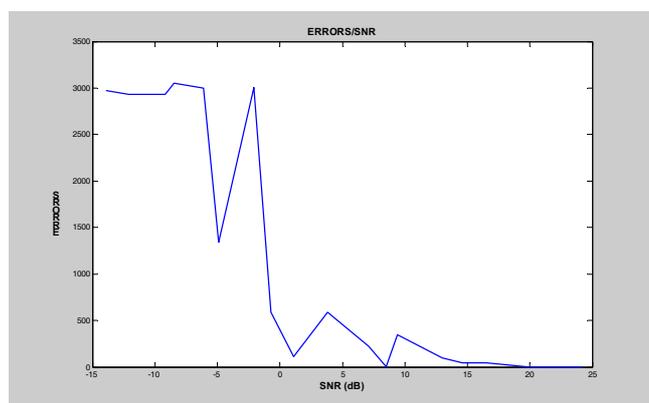


Fig. 6. Data rate 226 b/s: Graphic showing the number of errors/ping committed at different SNR. Distance between Tx and Rx equal to 7.5 km. Speed: 0 m/s.

In TABLE II results about some experiments with varying distance, speed and SNR are presented. Each row is related to the transmission of one ping containing 5670 information bits.

Tx-Rx [km]	Speed [m/s]	SNR [dB]	Errors
15	drifting	9.8	3
15	drifting	4.1	162
15	drifting	6	844
7.5	0	20.2	0
7.5	0	16.5	44
7.5	0	8.5	6
7.5	0	1.1	111
7.5	0	-0.7	590

TABLE II. Errors related to different working conditions (226 b/s)

5 Conclusion

The results show that the developed communication algorithm is able to handle the multipath phenomenon and the Doppler effect, allowing one to achieve good performances for distances up to 50 km at a rate of 13 bps and with $\text{SNR} > -9$ dB. Some problems occur at the higher data rate (226 bps). In particular the multipath phenomenon is the problem that mainly affects the algorithm performances. In the analyzed data, if the multipath is smaller than the bit duration and the $\text{SNR} > 0$, the algorithm performance are good. When these conditions are not satisfied a threshold effect takes place: the errors dramatically increase making impossible the correct estimation of the message.

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