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Frame Detection and Synchronization for a SIMO Receiver in presence of Doppler Shift for Underwater Acoustic Communications

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Abstract—In underwater acoustic communications, the received signal is strongly affected by Doppler shift due to the relative motion between the transmitter and the receiver. The signal is received compressed or dilated making it hard to detect and synchronize. Therefore, the doppler shift needs to be estimated and compensated. In this article, a new multisensor method to jointly estimate the Doppler shift, detect and synchronize the signal is proposed.

Index Terms—underwater acoustic communications, Doppler shift, synchronization, detection.

I. INTRODUCTION

The underwater acoustic communication channel is often considered as one of the harshest communication channel. It is characterized by three major factors: an attenuation proportional to the signal frequency, time-varying multipath and low speed of propagation ($1500m.s^{-1}$) [1]. The low speed of propagation increases the multipath and Doppler effects. Indeed the delay spread can be quite important. Therefore, the Doppler not only creates a shift of the carrier frequency but also time compression/dilatation. The Doppler for a constant speed between the receiver and the transmitter is equal to:

$$d = 1 - \frac{v}{c} \quad (1)$$

where v is the relative speed between the emitter and the receiver and c is the speed of sound underwater (approximately $1500m.s^{-1}$).

The underwater acoustic communication channel is doubly selective in time and frequency. All together, these phenomena make it hard to detect the signal. The Doppler shift needs to be compensated. Indeed, because of time compression/dilatation, detecting the signal and synchronizing it may be impossible without Doppler correction. A common approach is to use linear frequency modulated (LFM) signals around the transmitted frame [2]. By comparing the delay between the LFM signals at the receiver with the expected delay, it is possible to estimate the Doppler and compensate it by interpolation.

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LFM are known to be insensitive to Doppler shift making it interesting to use [3]. One can also estimate the Doppler shift and follow its evolution using the channel delay [3]. Unlike [2], this method doesn't need any frame synchronization to work.

In this article, Doppler estimation is done using a pilot signal. Main Doppler shift is considered equal for all paths. [4] shows that Doppler can be different for each path. However if a path is stronger than other paths, the optimal resampling factor is very close to the resampling factor of the strongest path. The proposed method assumes a major Doppler shift without considering differential Doppler shift variations due for instance to the movement of the waves.

In this paper, a new method to jointly estimate Doppler, detect and synchronize the signal in a single input multiple output (SIMO) context is presented. In comparison with the state of the art, the innovation lies in the use of the spatial diversity before the frame detection. This method expands the single input single output (SISO) model and use the space diversity brought by multisensors to improve performances at low signal to noise ratio (SNR). This method was tested in simulation and using data recorded at sea in Brest harbor.

This paper is organized in 3 parts. First the SISO and SIMO models are explained. Then the detection part is detailed. Finally the results are presented.

II. DOPPLER FILTER BANK

A. SISO model

In a SISO system, one way to evaluate the Doppler shift is to use a bank of matched filters [2]. Each filter is a time compression/dilatation of the pilot signal. Therefore, each filter simulates one possible Doppler shift. Theses filters can be created by resampling the pilot signal.

Let $s_0(t)$ be the OFDM pilot signal:

$$s_0(t) = \exp(j2\pi f_0 t) \sum_{n=0}^{N-1} q_0^{(n)} \exp(j2\pi n B t) g(t) \quad (2)$$

where N is the number of subcarriers, $q_0^{(n)}$ is the n^{th} symbol, B is the subcarrier spacing, $g(t)$ is the pulse-shaping filter and f_0 is the non-centered carrier frequency. Once affected by a Doppler shift $d = 1 - \frac{v}{c}$, it becomes:

$$s_0(t, v) = \exp(j2\pi f_0 t d) \sum_{n=0}^{N-1} q_0^{(n)} \exp(j2\pi n B t d) g(t d) \quad (3)$$

Matched filters of $s_0(t, v)$ are created. Then the cross-correlation between the bank filter and the received signal is realized.

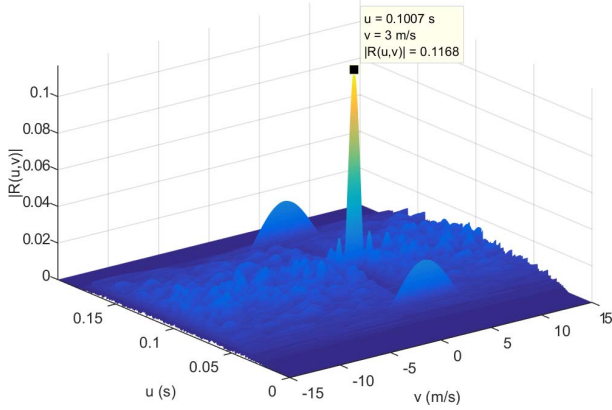


Fig. 1. Bank filter simulation result $R(u, v)$ (Passband 16-20 kHz, $v_0 = 3m.s^{-1}$, $u_0 = 0.1s$), AWGN channel

In Fig. 1, $R(u, v)$ is the result of the cross-correlation between the filters and the received signal. It depends on the delay and the relative speed d used to create the filters. In Fig. 1, a high correlation peak between the received signal and the filter simulating a $3m.s^{-1}$ Doppler shift is present. 2 lobes can be seen. They are the result of the cyclic prefix correlation.

The estimated Doppler shift is the one used to create the filter giving the highest correlation peak. The precision of the result depends on the number of matched filters in the filter bank. Obviously having more filters also means a higher computational cost. The length of the pilot signal also influences the performances of the proposed solution. A longer pilot signal means a better correlation result. However the length of the pilot signal is limited by many factors. First, the Doppler shift changes over time which will affect the pilot signal. Usually, the pilot signal is used to make a first estimation of the Doppler shift. Then the evolution of the Doppler shift is tracked for each symbol [5]. Second, the length of the pilot will affect the computational complexity of the solution. A longer signal means more calculations. Finally, the pilot doesn't hold any usefull information and thus decrease the overall throughput. The correlation output can also be used to synchronize the signal in a similar way as the one used in CP-OFDM [6]. The highest correlation peak is used for synchronization purpose. In a multipath environment, the receiver is synchronized on the most powerful path. Finally the cell-averaging constant false alarm rate(CA-CFAR) method

is used to detect the signal by comparing the correlation peak with a SNR-linked threshold [7]. This detection method will be further detailed in part 3.

The SISO model is sensitive to the time varying SNR and to the position of the transducers because the channel is also spatially selective. To solve this issue and keep on detecting the signal at lower SNR, diversity can be used by adding sensors at the receiver.

B. SIMO model

The SIMO model is a multisensor expansion of the previously presented filter bank model. This method uses spatial diversity provided by all the sensors. Signals received on each sensor may have different SNR since the reception is spatially selective. In SIMO, the filter bank is created in a similar way as in SISO. However, the filter bank is applied independantly on each sensor. Therefore we get multiple correlation matrices $R_i(u, v)$ where $i = 1, \dots, I$ and I is the number of sensors. All these matrices are then combined. The combination process is really important since it will decide how spatial diversity is used. Here the realized combination is a sum of all the matrices for each sensor. To maximize the result, correlation peak of each matrix must be aligned before summation. This alignment is used to get the highest correlation peak over a maximum delay thus improving the detection rate.

Alignment processing is done by searching the sensors summation maximum for differents delays:

$$\max_{\tau_i} \sum_{i=1}^I |R_i(u - \tau_i, v)|, 0 \leq \tau_i \leq \tau \quad (4)$$

One way to solve this is to use a greedy algorithm by trying all τ_i possible delays that are less than a maximal delay τ . This algorithm has however a high computational complexity. That is why the use of a sliding window is proposed to reduce the computational cost. After windowing process, we get:

$$M_i(t, v) = \max_{t \leq u \leq t + \tau} |R_i(u, v)| \quad (5)$$

Each sample of M_i is equal to the maximum value of R_i inside a time window of τ . τ is equal to the maximum possible delay between sensors. Using (5), (4) becomes:

$$M(t, v) = \sum_{i=1}^I M_i(t, v) \quad (6)$$

Let us take a system with $I = 4$ sensors at the receiver. A 80 ms OFDM signal pilot is used. Let $R_i(u, v_0)$ be the filter bank output for sensor i and a relative speed v_0 .

In Fig. 2, we can see the effect of multipath with a delay spread of 10ms. Fig. 2 - 5 were obtained through at sea experiments.

To align the correlator outputs, we use the sliding window method. $M_i(t, v)$ signals are represented in Fig. 3. The window is useful to get the maximal sum for every possible delay shift τ_i and thus to find the time delay for each sensor.

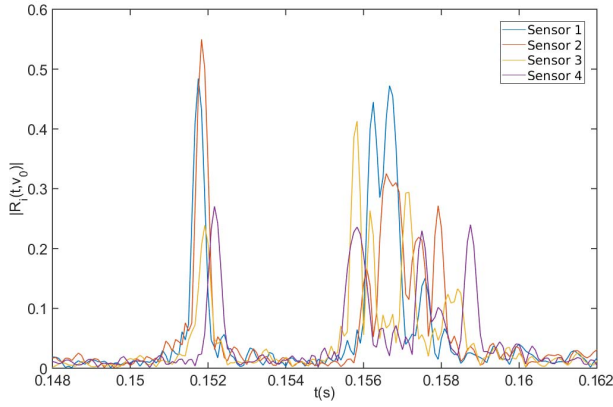


Fig. 2. Bank filter output for each sensor and $v = v_0$

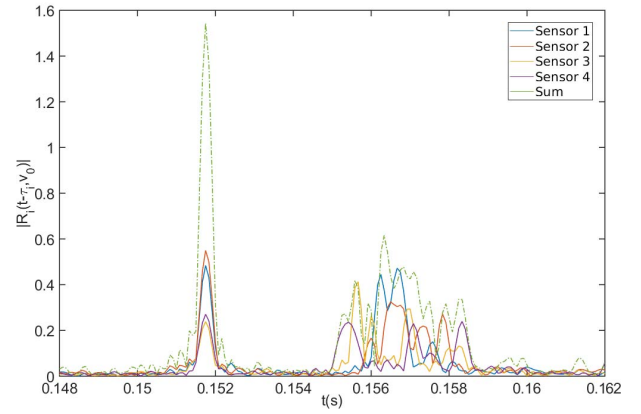


Fig. 4. Aligning correlations output and summation

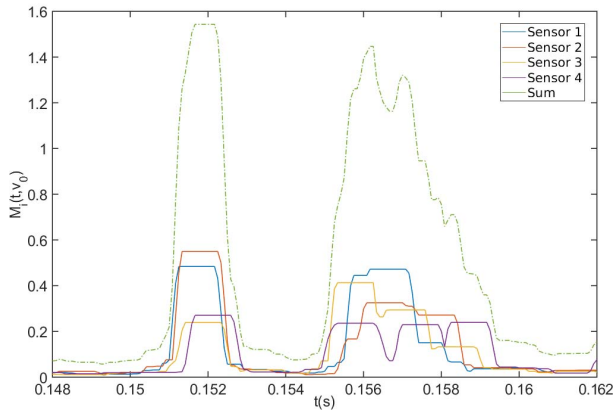


Fig. 3. Maximum sliding window and summation, $\tau = 1ms$

In Fig. 4, the correlation sum after alignment is shown. As one can see, the combination enhances the correlation peak without changing much the noise level. Therefore, spatial diversity brings a SNR gain before detection thus proving the advantage of this method. Like the SISO model, this summation can be used to realize synchronization on the strongest path and detect the frame which is presented in the next part.

III. FRAME DETECTION

In underwater acoustic communications, SNR can quickly fluctuate. Therefore, for detection purposes, an adaptive threshold is needed. CA-CFAR can answer this issue [7]. In CA-CFAR, the highest correlation peak is compared to the surrounding samples. In our case, CA-CFAR is applied to the correlation output with the highest correlation peak in SISO or to the summation of the highest peaks in SIMO. The threshold we get from CA-CFAR is compared to the correlation maximum.

The most important and difficult point is how the threshold is computed. CA-CFAR threshold is defined as stated below.

Let R_U be the correlation maximum of the filter output with the highest peak for the SISO model or the maximum of the

summation with the highest peak for the SIMO model (which would be the highest peak of the sum in Fig. 4), G a guard interval and L the reference window. CA-CFAR threshold S is calculated:

$$S_1 = \frac{1}{L} \sum_{n=1}^L |R_{U-G-n}|^2 \quad (7)$$

$$S_2 = \frac{1}{L} \sum_{n=1}^L |R_{U+G+n}|^2 \quad (8)$$

$$S = \frac{S_1 + S_2}{2} \quad (9)$$

Guard interval G is used to take into account the spread of the correlation peak and avoid that the peak affects the threshold. Window L contains the samples used to compute the threshold. Correlation maximum is compared to the S multiplied by a constant depending on the false alarm rate [7]. A frame is detected when the correlation maximum is greater than the threshold.

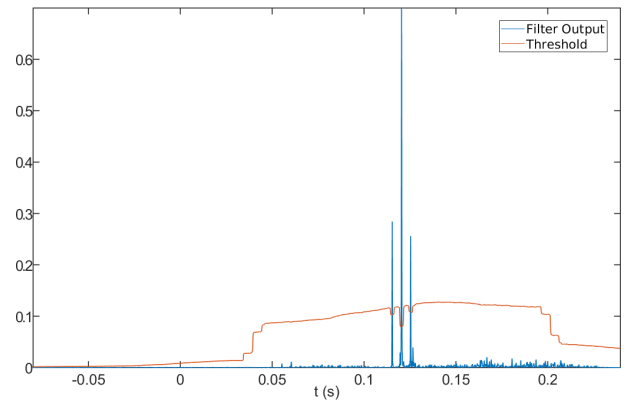


Fig. 5. CA-CFAR computed on matched filter output

As shown in Fig. 5, the threshold changes overtime. When looking at the transmitted signal part, the threshold is greater.

IV. EXPERIMENTATION

A. Experiments at sea

During tests at sea, the modem used was a OFDM modem [5]. Transmissions were made at a distance of 800m. Sent signals were recorded using 4 sensors separated from each other by approximately 50 cm. 20 frames were sent per transmission. Using this database, a detection benchmark in SISO and SIMO was made.

Transmissions had a strong SNR (around 30dB). Therefore, detection worked perfectly on all the collected data. To evaluate improvements brought in the SIMO model, we decided to add a white gaussian noise to the received signals. In underwater acoustic communications, noise is usually not white, however the proposed simulation lets us validate the improvements before further experiments at sea are done. The SISO modem was designed to work at a SNR greater or equal to 6dB. To test the improvements, a noise is added so SNR is below 6dB. The simulated noise is thus generated to have a SNR around 0dB on each sensor. Therefore we should not be able to detect the signal using only 1 sensor.

B. Results

Two transmissions have been analyzed. 20 frames per transmission have been sent with 25 symboles OFDM and 6192 bits per frame. [5] is used as receiver where robust synchronization and convolutional code are used to decode the information. A convolutional code with a $\frac{1}{2}$ rate was used. Results are summarized in two tables. Tables I and II display results for each sensor and for their combination. Bit error rate (BER) is specified. BER is computed on the detected frames. N/A means BER cannot be computed since no frame was detected.

TABLE I

RESULTS OF THE FIRST TRANSMISSION (DISTANCE OF 800M, FREQUENCY PASSBAND: 8 - 12 KHZ)

	sensor 1	sensor 2	sensor 3	sensor 4	SIMO
detected frames	0	0	9	7	20
mean BER	N/A	N/A	0,16	0,23	0,0027

TABLE II

RESULTS OF THE SECOND TRANSMISSION (DISTANCE OF 800M, FREQUENCY PASSBAND: 13 - 17 KHZ)

	sensor 1	sensor 2	sensor 3	sensor 4	SIMO
detected frames	0	3	2	2	20
mean BER	N/A	0,037	0,065	0,23	0,0004

Performance improvements can be seen on both tables. Indeed, sensors can only detect a few frames on their own but, using their combination all the transmitted frames are detected. BER also shows that the detected frames on SISO model were not properly decoded as expected. The SIMO

model uses spatial diversity to improve the detection and the BER.

V. CONCLUSION

In this article, a new method to jointly estimate the Doppler shift, detect and synchronize the signal for a SIMO receiver in underwater acoustic communications is proposed. This method is tested using recordings made at sea. The SIMO method was compared to the SISO one. Results show concrete improvements of this method over the SISO one and its efficiency at lower SNR to detect frames.

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