Ultrasonic beacon-based Local Positioning System using Loosely Synchronous codes

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Abstract **– This work presents the development of a Local Positioning System (LPS), based on the transmission of ultrasonic signals, which have been previously encoded by Loosely Synchronous (LS) codes. The LPS consists of several ultrasonic emitters located at known positions in the environment, and of a portable receiver that computes its position by measuring the Differences in Times of Arrival (DTOA) between a reference emitter and the others. LS codes exhibit an Interference Free Window (IFW) in the auto-correlation and cross-correlation functions. Therefore, if the relative time-offset of the codes are within the IFW, it is possible to have simultaneous emissions without interference, as well as to reduce the multipath effect.**

Keywords **– Acoustic LPS, asynchronous detection, DS-CDMA, LS-codes, IFW, ISI, MAI.**

I. Introduction

Local Positioning Systems (LPS) allow to determine the location of a person or object in a certain area and, by using ultrasonic transducers, a suitable resolution degree is obtained [1]. Most of them consist of a set of beacons situated at known positions in the environment, and synchronized by radio-frequency (RF). The receptor is placed in a mobile robot and measures the Times of Arrival (TOAs) of the ultrasonic signals, starting from the emission interval [2] [3] [4]. Nevertheless, the use of RF signals implies an increase of the power consumption, interferences, etc. In [5] it is proposed an LPS where only acoustic emissions are used. It determines the absolute position of a mobile robot by hyperbolic triangulation of the distances obtained from the measurement of the Difference in TOAs (DTOAs) among a reference beacon (the nearest one) and the others, considering that all of them emit simultaneously and in a continuous way. Cancelation of interferences among simultaneous emissions is possible by using the SS-CDMA (Spread Spectrum Code Division Multiple Access) technique. Thus, a different orthogonal code is assigned to every beacon. The receiver on board the robot carries out the simultaneous correlations with the codes associated to every beacon, in order to detect the DTOAs between the reference beacon and the others. As the mobile robot does not need to know the emission instant, the RF signal can be supressed (it is enough a common synchronism among all the beacons).

The effectiveness of these systems strongly depends on the SS codes that codify the ultrasonic emissions. Those codes should provide very low cross-correlation (CC) values to avoid the Multiple Access Interference (MAI); and very low auto-correlation (AC) sidelobes to reduce the Inter-Symbol-Interference (ISI). In absolute positioning with ultrasounds, several previous works use pseudo-random (PR) sequences: Gold sequences [1] [6], and Kasami sequences [5]. Other works that codify the ultrasonic signal for the detection of obstacles in robotics use Barker codes [7], Golay codes [8] or Complementary Sets of M sequences (M-CSS) [9]. None of these sequences eliminate both ISI and MAI completely and simultaneously [10]. Golay pairs and M-CSS eliminate them by using more than one sequence per user, what implies some restrictions in the AC and CC functions [11].

Loosely Synchronous (LS) codes [12] exhibit an Interference Free Window (IFW), where the aperiodic AC sidelobes and CC values are zero. Consequently, if the time-offsets between the codes, expressed in terms of number of chips intervals, are within the IFW, both ISI and MAI can be eliminated thoroughly. Furthermore, the correlation of these codes can be carried out by means of an Efficient LS Correlator (ELSC) [13], which significantly reduces the total number of operations performed, in comparison with an straight-forward matched filter implementation. Thus, real-time operation can be possible without the aid of high complexity hardware.

This paper proposes the design of a LPS, which uses LS sequences to encode the ultrasonic signals. The paper is organized as follows: Section II presents the global arquitecture of the LPS. In Section III LS codes are described. Some results are shown in Section IV. Finally, conclusions are outlined in

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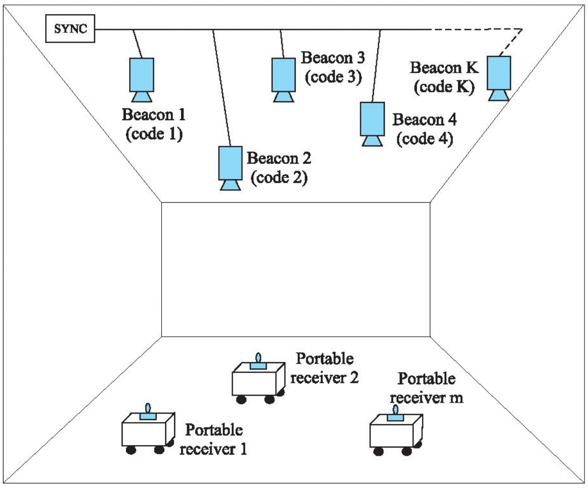

Fig. 1. SCHEMATIC REPRESENTATION OF THE LPS.

Section V.

II. GLOBAL STRUCTURE

Fig. 1 shows a schematic representation of the global structure of the proposed LPS. A set of hardware synchronized beacons (there exist a wire joining them) are placed at known positions of the environment, and all of them cover a determined area by emitting periodically. A non-limited number of portable receivers compute their own positions from the measurement of DTOAs, according to an hyperbolic triangulation algorithm (all the signals are asynchronously detected). At every position, the specific portable receiver has to detect at least 4 beacons for 2D positioning, or 5 beacons for 3D positioning.

In order to avoid multipath and multi-user interferences, the SS-CDMA technique is used, by encoding the ultrasonic signal with a different LS code for every beacon. On the other hand, the ultrasonic transducer used to emit the codes imposes its frequency response. Thus, it is necessary to modulate the signal to be emitted to place its spectrum at the maximum frequency response of the emitter. Concerning the reception process, all the signals can be simultaneously received by a group of portable detection modules (the total number depends on the particular application). Every module is able to distinguish between the different transmissions thanks to LS properties. It is important to notice that the received transmissions should arrive within the IFW to mitigate ISI and MAI. The detection process carried out in these modules involves four different tasks, namely, demodulation, efficient correlation, peak detection and positioning algorithm, as can be seen in Fig. 2.

The acquisition system converts the signal received by the ultrasonic transducer into a digital signal, which is demodulated to extract the transmitted information from the received signal. As there is no temporal reference in the receiver, the non-coherent demodulation is carried out by digital correlation with the modulation symbol. Later, K correlators simultaneously

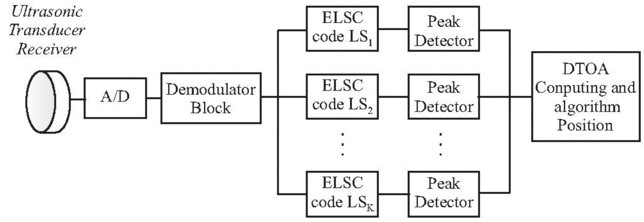

Fig. 2. BLOCK DIAGRAM OF THE RECEPTION STAGE.

correlate the demodulated signal with the K ideal emitted LS sequences. These correlations are performed by an efficient correlation system (ELSC) that notably decreases the total number of operations to carry out. In the precise moment at which the last sample of a received sequence is processed, a peak in the correlator for this LS sequence is obtained. A peak detector confirms the maximum values exceeding a static threshold, assuming that there is not a higher peak in the neighborhood. The maximum value nearest to time origin determines the beacon reference. The DTOAs between this reference beacon and the others are obtained by computing the difference in samples among the other maximum values in the different correlator outputs, and by multiplying them by the sampling frequency. The resulting values are used in the positioning algorithm to determine the robot's absolute position.

III. LS CODES

In [12] is proposed a method to construct LS codes from the well-known Golay pairs. It basically consists of linking with a specific order and directly or negated, depending on the coefficients of a Hadamard matrix, the sequences of two orthogonal Golay pairs of length N. Also, a set of W_0 zeros has to be inserted in the middle of the LS code to obtain the IFW in the correlation functions. Thus, it is obtained a set of K LS codes $\{G = g_k[l]; 1 \le k \le K; 0 \le l \le L-1\}$ with length $L = KN + W_0$, composed of $g_k[l] = \{0, \pm 1\}$ elements, and with aperiodic correlation functions equal to zero in a certain vicinity of the zero shift, that is:

$$R_{g_{k_1},g_{k_2}}[m] = \sum_{i=0}^{L-1} g_{k_1}[i] g_{k_2}[i+m] =$$
$$\begin{cases} K \cdot N, & \text{for} \quad m = 0, \quad k_1 = k_2 \\ 0, & \text{for} \quad 1 \le |m| \le W_0, \quad k_1 = k_2 \\ 0, & \text{for} \quad 0 \le |m| \le W_0, \quad k_1 \ne k_2 \end{cases} \tag{1}$$

Where $R_{g_{k_1},g_{k_2}}$ is the aperiodic correlation among g_{k_1} and g_{k_2} (note that the AC function is obtained when $k_1 = k_2$, whereas the CC function when $k_1 \ne k_2$); $K = 2^n$, being n any natural number, is the number of available LS codes with orthogonal properties in the IFW, that is, the maximum number of beacons that can simultaneously access to the medium; as has been stated before, N is the length of the Golay pairs used in the construction of LS codes; and $2W_0 + 1$ denotes the length of the IFW, being $W_0 \le N - 1$.

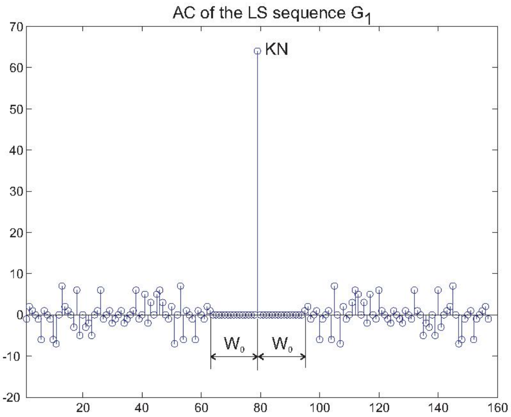

Fig. 3. AC FUNCTION FOR A SEQUENCE LS(16,4,15).

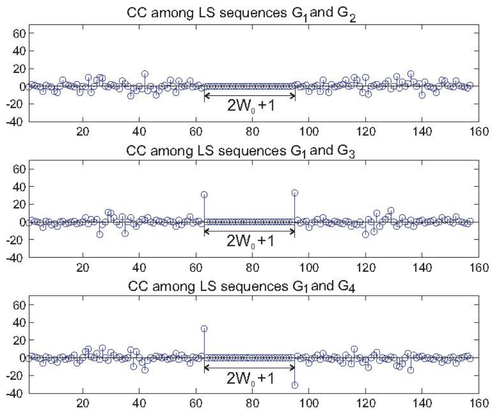

Fig. 4. CC FUNCTIONS AMONG THE SEQUENCES OF A SET GENERATED AS LS(16,4,15).

Since every LS family set can be defined by its parameters N, K and W_0, notation $LS(N,K,W_0)$ has been adopted. In Fig. 3 is shown the aperiodic AC of a $LS(16,4,15)$; whereas in Fig. 4 is depicted the aperiodic CC among different $LS(16,4,15)$ from the same set. It can be observed that interferences outside the IFW can be higher, even more than those of classic PR codes, so it is important to assure that the maximum dispersion delay of the channel (denoted by T_d) satisfy $T_d \leq W_0$ to minimize ISI and MAI interferences.

A. LS characterization outside the IFW

Several simulations have been carried out in order to study the performance of LS codes outside the IFW. Both the number of interferences outside the IFW and their magnitude have been evaluated.

It is well known that LS codes exhibit an IFW where neither AC sidelobes nor CC interferences appear. Outside the IFW there also exist zones with no interferences. Through experimental tests, it has been checked that the zone out of the IFW consists of approximately 75.72% of interferences (with an standard deviation of $\sigma = 0.0173$), and 24.28% of zeros. In Fig. 5 the percentage of CC interferences in LS sequences is represented for K simultaneously users. It can be observed that, the more users there are, the higher percentage of interferences in the specific sequence is.

To evaluate the magnitude of the AC sidelobes and CC values outside the IFW, the bound θ of LS sequences has been represented in Fig. 6. These bounds θ values are calculated according to (2) and expressed in percentages. Note that θ_{AC} corresponds to the AC bound, whereas θ_{CC} to the CC bound. The more simultaneous users there are, the higher bounds are obtained: 75.11% and 87.57% for $K = 16$ and $K = 32$ users respectively. It should be noted that, for a specific number of users, the percentage on interferences and correlation bounds are not affected by the sequence length (and specifically, they are not affected by the length N of the initial Golay codes). Thus, the length N has to be selected so as to have an enough IFW for the specific application, with the shortest LS codes (the larger a code is, the more resources and processing time are required for its correlation).

$$\theta = \max(\theta_{AC}, \theta_{CC}) \begin{cases} \theta_{AC} = \dfrac{\max\left\{\left\| R_{g_{k_1},g_{k_1}}[m] \right\|\right\} \forall m \neq 0}{R_{g_{k_1},g_{k_1}}[0]} \\ \theta_{CC} = \dfrac{\max\left\{\left\| R_{g_{k_1},g_{k_2}}[m] \right\|\right\} \forall m}{R_{g_{k_1},g_{k_1}}[0]} \end{cases} \quad (2)$$

A search for LS codes with the lowest bounds outside the IFW has been carried out, so as to reduce the interference in case that any echo falls outside the IFW. It has been checked that bounds obtained with LS codes generated with the same parameters (N, K, W_0) but from different Golay pairs, are very similar. When the number k of users is not a power of two, a set G with K LS codes, where K is the nearest power of two higher than k, has to be generated. In this case, it is possible to select the k LS codes in the set G with lower bounds. However it is not worthy to generate LS codes with $K > 2k$: in case that N is maintained constant, it means an unnecessary increment of the code length L without a better bound; and in case that N is reduced to maintain the length L constant, higher bounds are obtained.

To improve the performance of LS codes, it is also possible an enlargement of the IFW by inserting more zeros than $N - 1$ ($W_0 > N - 1$). It means an increase of the code length while maintaining the AC peak value, and the apparition of a set of controlled interferences within the IFW. This controlled interferences can be later eliminated by using ISI and MAI cancellation techniques [15].

B. Efficient LS Correlator

When longer LS sequences have to be processed in real-time, the increasing in the computational load demands the use of efficient correlators, able to perform the detection of these sequences with affordable computational cost. In [13] an efficient correlator for LS sequences, named ELSC, is proposed. It notably decreases the total number of performed operations, in comparison with a straight-forward implementation, as can

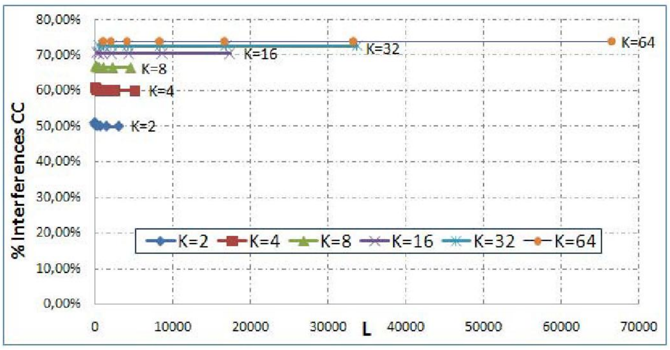

Fig. 5. NONZERO VALUES OF CC OF LS SEQUENCES AS A FUNCTION OF NUMBER OF USERS K AND CODE LENGTH L.

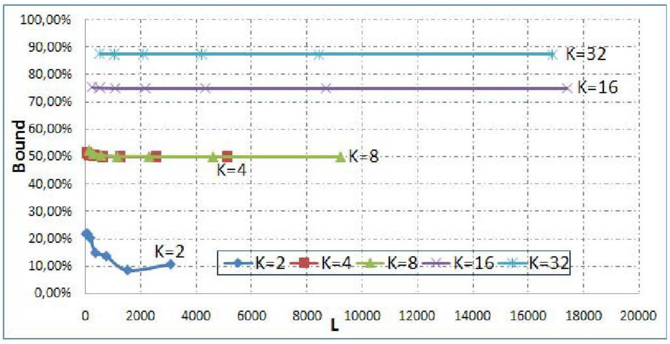

Fig. 6. BOUND IN LS SEQUENCES AS A FUNCTION OF NUMBER OF USERS K AND CODE LENGTH L.

TABLE I.

OPERATIONS TO PERFORM FOR THE CORRELATION OF LS CODES, USING AN STRAIGHTFORWARD IMPLEMENTATION AND AN ELSC.

Implementation	Multiplications	Additions
Straight-forward	$L = KN + W_0$	$L - 1 = KN + W_0 - 1$
ELSC	$2log_2 N + K$	$4log_2 N + 1$

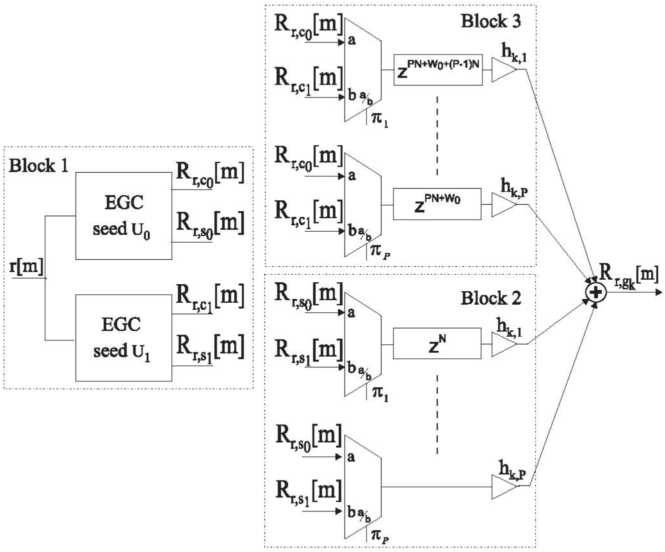

Fig. 7. BLOCK DIAGRAM OF THE EFFICIENT LOOSELY SYNCHRONIZED CORRELATOR.

be observed in Table I. Fig. 7 depicts the block diagram of the ELSC. It exploits the Efficient Golay Correlator (EGC) developed in [16] to simplify the correlation process. Two EGCs are used to simultaneously perform the correlation among the input LS sequence and the two orthogonal pairs composing it. Afterwards, the corresponding outputs of the EGCs are delayed, and added or subtracted according to the values of a binary vector π and the coefficients $h_{i,j}$ of a Hadamard matrix H.

Another advantage is that this correlator can be easily implemented in configurable hardware to achieve real-time operation (see [13] for further details).

IV. RESULTS

The proposed LPS has been simulated to verify its feasibility. The system is composed by a group of five beacons. Every beacon has an assigned $LS(128, 8, 127)$: a 1151-bit LS code with an IFW of 255 bits. These codes have been BPSK modulated by using a symbol with one period of a 50 kHz square signal. Thus, the duration of the signals is $1151 \cdot 20$ μs= 23.02 ms, and the maximum delay among the arrival of the different emissions is $T_{d_{max}} = 127 \cdot 20$ μs= 2.54 ms. The beacons' location has been chosen so as to assure that this time $T_{d_{max}}$ is not exceeded. Taking this into account, the five beacons are placed over the floor with a height of 3 m, and into a 1 m $\times$ 1 m surface, whereas the robot has been located at the coordinates ($x = 0.2$ m, $y = 0.1$ m, $z = 0.3$ m), as can be seen in Fig. 8.

All the beacons are synchronized by a common clock and they periodically emit a LS code every 50 ms. The emissions are acquired and digitalized with a sampling frequency of 500 kHz. The resulting signal is demodulated and the corresponding correlations are carried out. Fig. 9 shows the signal received assuming no noise, and Fig. 10 depicts the outputs of every correlator. Beacon 1 has the maximum value near the time origin, so it is the reference beacon. It can be also observed the IFW in every output correlator. Since all the echoes arrive in a time lower than $T_{d_{max}}$, both ISI and MAI interferences are mitigated in the area of the IFW. Outside the IFW the AC sidelobes and CC values are elevated, and can cause serious problems due to MAI and multipath interference in case of asynchronous detection. To avoid this, a special frame or window structure should be used: a maximum will be considered as a valid peak if its value is higher then a determined threshold and if it is surrounded by a window with only noise, but not interferences. Fig. 11 represents an enlargement of Fig. 10, where the distance among AC peaks can be observed.

In order to verify how the proposed system can operate in presence of noise, a similar detection has been carried out with a signal-to-noise ratio of SNR= 0 dB. Fig. 12 shows the reception after the simultaneous emission of the five beacons, and Fig. 13 the correlation outputs. It can be observed that the detection of the different echoes is still achieved by the system.

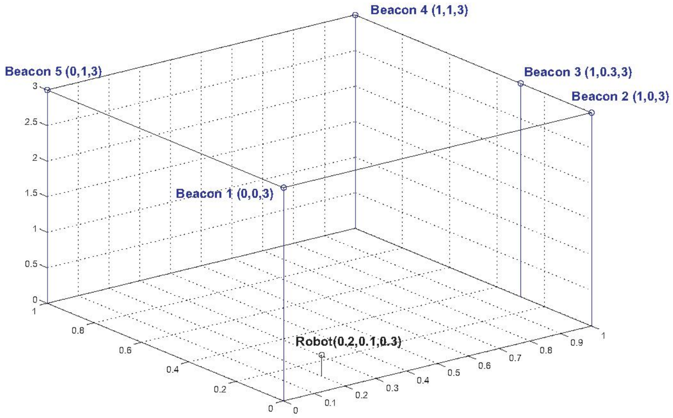

Fig. 8. SCHEME OF THE BEACON DISTRIBUTION AND OF THE POSITION OF THE MOBILE RECEIVER.

Finally, the five beacons are located into a $5\ \mathrm{m} \times 5\ \mathrm{m}$ surface, with a height of 3 m. The robot maintain its former coordinates, and the SNR= 0 dB. This new beacon distribution is designed in such way that the delay between the arrivals of the different emissions can be higher than $T_{d_{max}}$. In this example, the emissions from beacons 2, 4 and 5 arrive outside the IFW of beacon 1 and 2 (see Fig. 14). It is not possible to determine the arrival of echoes corresponding to beacons 2, 4 and 5, so the DTOAs can not be computed, and therefore, the position of the portable receiver can not be obtained.

V. CONCLUSIONS

A local positioning system based on the use of LS sequences has been presented. It consists of using simultaneous emission from ultrasonic beacons. Every beacon is encoded with a LS sequence, which has the particularity of having a perfect auto-correlation and cross-correlation functions in the IFW. Every beacon periodically and continuously transmits its corresponding sequence. The mobile receiver does not require to know the emission instant, and therefore, it is not necessary a synchronism trigger signal between the receiver and the beacons. The system allows a non-limited number of mobile receivers working in the same environment, and thanks to the use of efficient correlators, real-time operation is achieved.

The suitability of LS codes for LPS has been analyzed. If the relative time-offsets between the codes are within the IFW, it is possible to easily identify the AC peaks, as both ISI and MAI are considerable reduced, even in case of low signal-to-noise ratios. Nevertheless, AC sidelobes and CC values are considerable outside the IFW, which is critical for asynchronous systems. A special analysis window is used in the reception to restrain the aperiodic interference components outside the IFW. As well as this, an analysis of the number of interferences and its magnitude outside the IFW has been carried out. Finally, the performance of the system has been tested by simulation.

ACKNOWLEDGMENT

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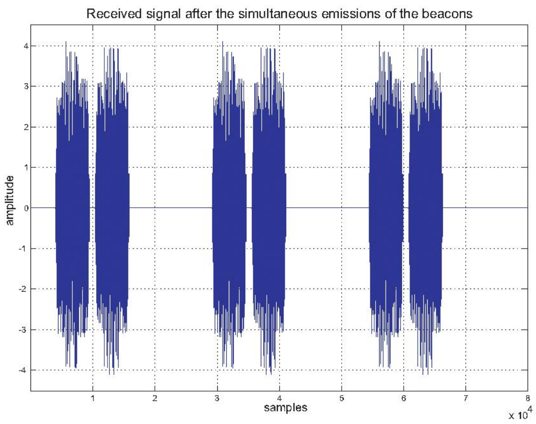

Fig. 9. SIGNAL RECEIVED WITH NO NOISE.

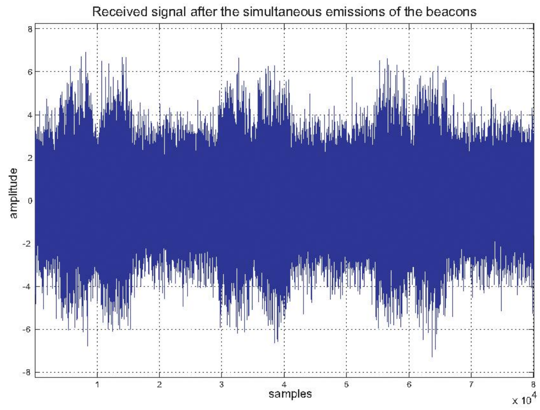

Fig. 12. SIGNAL RECEIVED WITH A SNR$= 0\ dB$.

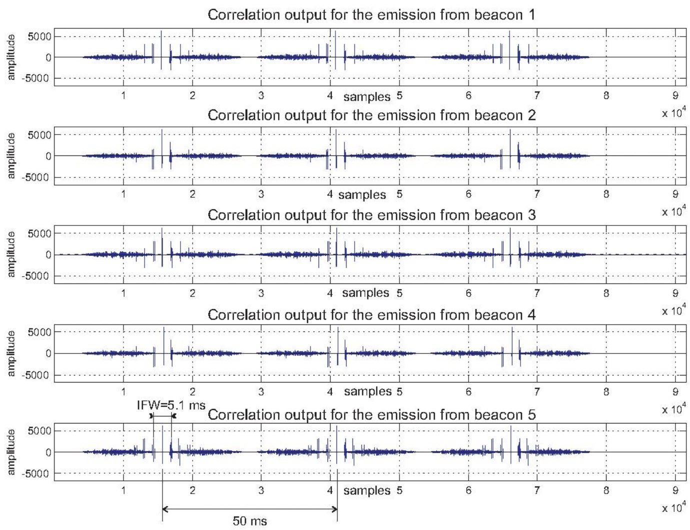

Fig. 10. CORRELATION OUTPUT FOR THE EMISSION OF EVERY BEACON IN CASE OF NO NOISE.

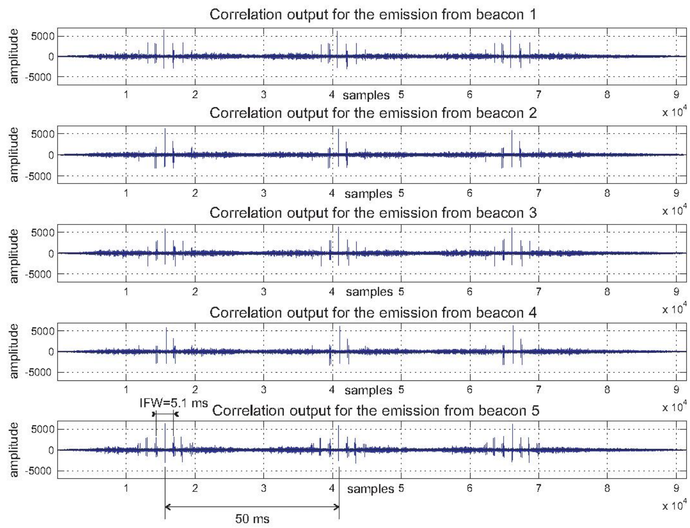

Fig. 13. CORRELATION OUTPUT FOR THE EMISSION OF EVERY BEACON IN CASE OF A SNR$= 0\ dB$.

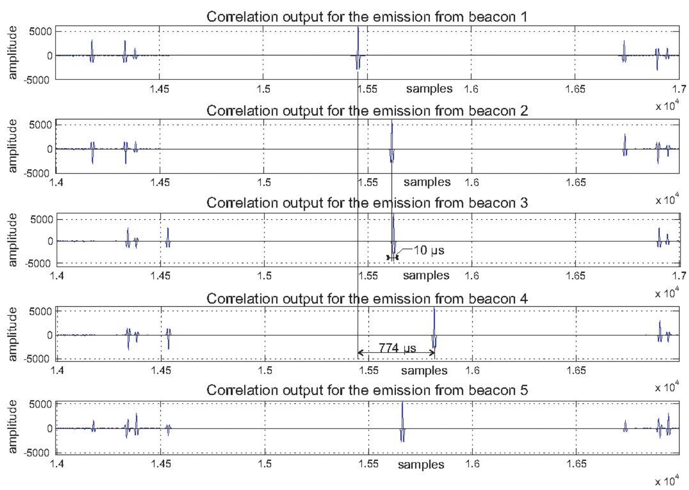

Fig. 11. ENLARGEMENT OF FIG. 10.

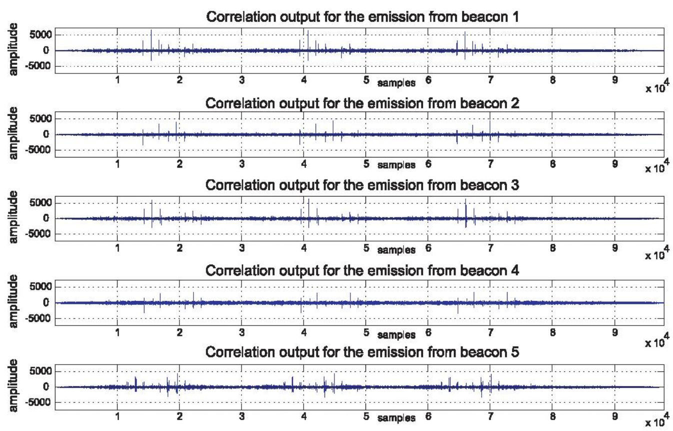

Fig. 14. CORRELATION OUTPUTS IN A SYSTEM WHERE THE TIME-OFFSET BETWEEN SEQUENCES IS LARGER THAN THE IFW.