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SEPARATION OF CONCURRENT ECHOES DEPENDING ON THE EMITTING SOURCE USING DS-CDMA

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ABSTRACT
Many ultrasonic systems based on time-of-flight measurements use signals encoded with binary sequences with similar properties to Gaussian noise. Afterwards, the corresponding echoes are detected correlating the received signal with the original sequence. Thus, an improvement of temporal precision, spatial resolution and robustness to noise is obtained, in comparison with methods based on threshold detection. Furthermore, it could be interesting to have several transducers emitting ultrasound waves over the same spatial zone, and at the same time, allowing measurements from different locations simultaneously. These ultrasonic systems need an asynchronous detection as the echoes could arrive at any moment depending on the transducer and reflector positions. In such case sequences (one in every emitter) with a high Auto-Correlation function and low sidelobes should be used, as well as with low aperiodic Cross-Correlation values among them. As a result, it is possible to detect, and separate according with the original source of the emitted signal, all the echoes even in the case of high noise or attenuation. In this work, three different systems are presented based on Kasami sequences, Complementary Sets of sequences and Loosely Synchronized (LS) sequences. All of them were originally intended for the use in ultrasonic Local Positioning Systems.

INTRODUCTION
The incorporation of the encoding and processing techniques used in radar theory into airborne sonars is a major step in the evolution of these systems, as it supposes a notable improvement in features such as their temporal precision, spatial resolution and robustness to noise. On the other hand, the capability of simultaneous emission through an appropriate selection of the codes to be emitted is very useful in those systems that require a set of measurements made under similar conditions, and where these conditions change very fast, as is the case of a local positioning system where the mobile robot or object to be localised is normally moving. Furthermore, it is important to have efficient algorithms to perform the correlations of the acquired signals, so they can be easily implemented on reconfigurable hardware to achieve real-time operation.

The effectiveness of the DS-CDMA technique depends on the properties of the used spreading codes, requiring ideal properties of autocorrelation (AC) and cross-correlation (CC). Many algorithms have been designed to generate codes, but not all of them meet these ideal properties simultaneously. Examples are the Pseudo-Random sequences [1], Barker codes [2], Golay sequences [3], sets of complementary sequences [4], etc. However these systems are interference limited. There exists Inter-Symbol-Interference (ISI) due to the non zero auto-correlation (AC) sidelobes of the used sequences. They also have Multiple-Access-Interference (MAI) due to the non zero cross-correlations (CC) values. To avoid the effects of both ISI and MAI, the sidelobes of the AC and the CC values should be as small as possible.
Barker codes [2] have been widely used due to their good aperiodic AC. However, their maximal length is limited, so it is not possible to detect them in case of high noise. Furthermore,

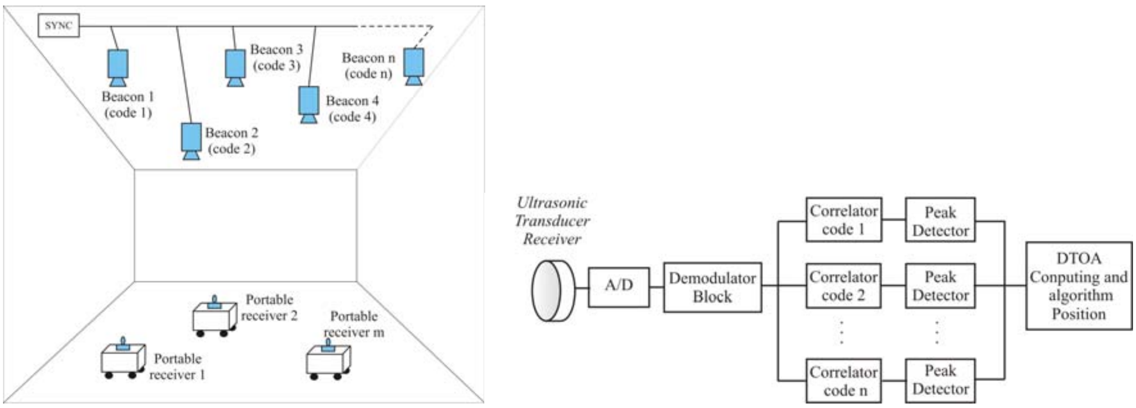
there are no Barker codes with low CC among them. Pseudo-random sequences such as m-sequences, Gold codes or Kasami codes, exhibit non zero off-peak AC and CC values in the case of asynchronous transmissions. Another possibility is Golay pairs, which have good aperiodic correlation properties, and their length is not limited. Nevertheless, they provide only two mutually orthogonal pairs, which is not useful for multi-user environments. Complementary sets of M sequences (M-CSS) are a generalization of Golay codes containing more than two sequences. The elimination of the constraint in the number of sequences of a set yields on a high process gain and also M mutually orthogonal sets. To achieve these goals, it is necessary to add the AC functions of the sequences of the set, or the CC functions of the corresponding sequences in the M sets, respectively. The problem is that, in many systems, transducers have limited bandwidths, so it is not possible to transmit or receive the M sequences of the set simultaneously. Unfortunately, it implies an undesired increase of both ISI and MAI. The detection of Golay pairs or M-CSS can be performed by means of efficient correlation algorithms which notably decrease the computational load and hardware complexity [10]. Loosely Synchronized (LS) codes [6] exhibit an Interference Free Window (IFW), where the aperiodic AC sidelobes and CC values become zero. Consequently, ISI and MAI are completely reduced if the maximum transmission delay is less than the length of the IFW.

As the application of DS-CDMA in airborne ultrasonic systems deals with band-limited transducers and asynchronous detection, in this work, three kinds of sequences with the besr performance are presented: Kasami sequences, Complementary Sets of sequences and Loosely Synchronized (LS) sequences. All of them are here intended for the use in advanced ultrasonic sensors or in ultrasonic Local Positioning Systems.

The paper is organized as follows. Section II introduces the general structure and block diagram of the detection method. In Section III the aforementioned sequences for asynchronous detection are presented. Section IV shows how these sequences are used in LPS applications and, finally, some conclusions are outlined in Section V.

GLOBAL STRUCTURE OF THE ULTRASONIC SYSTEM

Fig. 1 shows a schematic representation of the global structure of a Local Positioning System (LPS). A set of hardware synchronized beacons are placed at known positions of the environment, and all of them cover a determined area by emitting periodically a coded sequence (a different code each beacon). A non-limited number of portable receivers compute their own positions from the measurement of Differences of Times Of Arrival (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.



a) b)

Figure 1.- LPS configuration (a) and signal processing in a receiver (b).

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 correlate the demodulated signal with the *K* ideal emitted sequences. In the precise moment at which the last sample of a received sequence is processed, a peak in the correlator for this sequence is obtained. A peak detector confirms the maximum values exceeding a threshold, assuming that there is not a higher peak in the neighborhood.

SEQUENCES FOR ASYNCHRONOUS DETECTION

The purpose of this section is to evaluate the performance of Kasami sequences, Complementary Sets of *M* Sequences (M-CSS) and Loosely Synchronized (LS) sequences as encoding sequences for an ultrasonic beacon-based Local Positioning System (LPS). As several transducers will emit ultrasound waves simultaneously over the same zone, the encoding sequences should bear very low cross-correlation (CC) values to provide adequate discrimination among users. This is critical to control the multiple-access-interferences (MAI) in situations where there are large differences in the relative power level of the received signals. Furthermore, the sequences should have sharp auto-correlation (AC) functions, with very low sidelobes, to minimise the inter-symbol-interference (ISI) and provide higher processing gains.

Small set of Kasami sequences

Small set of Kasami sequences were first discussed in [5] to improve the cross-correlation (CC) properties of other pseudo-random codes. Basically, the set of Kasami sequences consists of $2^{n/2}$ sequences with length $L=2^n-1$, being n an even integer, whose AC sidelobes and CC periodic functions take values from the set $\{-1, -2^{n/2}-1, 2^{n/2}-1\}$. Both the periodic and aperiodic maximum AC value is L; nevertheless, the other aperiodic correlation values are not within this set. The aperiodic correlation properties of Kasami codes are analyzed in [6]: the maximum odd CC value for any pair of Kasami sequences is $2^{n-1}+2^{(n-2)/2}+1$, whereas the maximum periodic CC value (also called even CC value) is $2^{n/2}+1$.

The correlation of Kasami sequences is carried out by means of straight-forward matched filter implementations, in case of short sequences, or by Fast-Fourier-Transforms (FFTs) in case of larger ones [8]. These implementations provide large processing cost; and in case of large amount of data to be processed, real-time operation is difficult to achieve.

Complementary Sets of *M* Sequences

M-CSS are sets of M sequences with length $L=M^N$ whose elements are either $\{+1,-1\}$, where $M=2^m$, being m and N any natural number different from zero. The addition of the aperiodic AC functions of the M sequences from that set is zero everywhere, except for the zero shift where has a maximum value of $M \bullet L$. Furthermore, it is possible to obtain M mutually orthogonal sets.

Nevertheless, since more than one sequence encodes a user, a bit emission order has to be used. This implies a degradation of the ideal AC and CC properties: neither the AC sidelobes, nor the CC values for two orthogonal sets are null anymore. As it is desirable that all the sequences in the set are equally affected by changes in the environment, a transmission method based on interleave their bits is carried out. In [9] this method it is compared with linking consecutively the sequences of the set; also a post-processing algorithm is proposed to reduce the degradation in the AC and CC values.

The detection of M-CSS can be done with efficient correlation algorithms that notably decrease the computational load and hardware complexity, in comparison with straight-forward implementations. The hardware implementation of this efficient correlator adapted to the transmission scheme by interleaving is analyzed in [10]. It has been checked that, for equally long interleaved sequences, less hardware resources are required for cases generated from M-CSS with low number *M* of sequences.

Loosely Synchronized Codes

LS codes exhibit an Interference Free Window (IFW), in a certain vicinity of the cero shift, where the aperiodic AC sidelobes and CC values become 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.

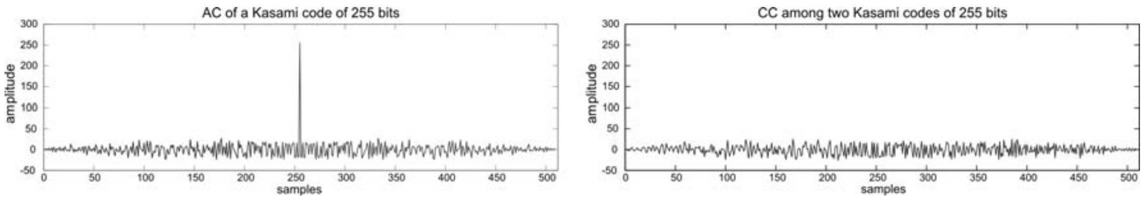
These codes exploit the properties of orthogonal 2-CSS (better known as Golay pairs) [11]. The notation $LS(N,K,W_0)$ has been adopted, where N is the length of the Golay pairs; K is the number of available codes with orthogonal properties in the IFW ($K=2^n$, n Є |N); and W_0 is the number of zeros to insert in the middle of the sequence during its construction (usually $W_0=N-1$). The total length of LS codes is given by $L=KN+W_0$, whereas the length of the IFW is given by $W=min\{2N-1,2W_0+1\}$. The AC peak of a LS sequence is equal to $K•N$, while the AC sidelobes and CC values within the IFW are zero. However, the AC and CC functions exhibit higher values outside the IFW than Kasami and M-CSS. Therefore, to minimize ISI and MAI the maximum dispersion of the channel (denoted by T_d) should satisfy $Td \leq W_0$.

The correlation of these codes can be carried out by means of an Efficient LS Correlator (ELSC) [12] which significantly reduces the total number of operations performed. Also, this correlator can be easily implemented in hardware configurable to achieve real-time operation.

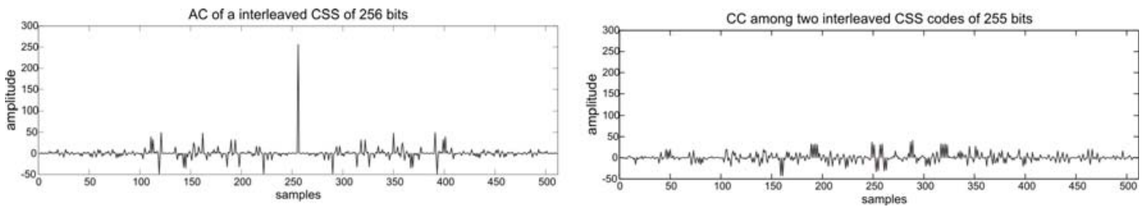
Sequences comparison

A direct comparison of the interferences caused by AC sidelobes and CC values in the three types of codes indicates that LS codes are more adequate, in case that the received transmissions arrive within the IFW. Nevertheless, if this cannot be assured, more serious MAI and multipath interferences will be encountered. Kasami codes are a good solution, as they posses low correlation interferences within all the correlation function (M-CSS's interferences are higher). However, when longer sequences have to be processed in real-time, the increasing in the computational load demands the use of efficient correlators, which does not exist for Kasami codes, so M-CSS have to be selected. Hence, it is inconclusively which of the three codes are better suited; they have to be chosen depending on the particular application characteristics.

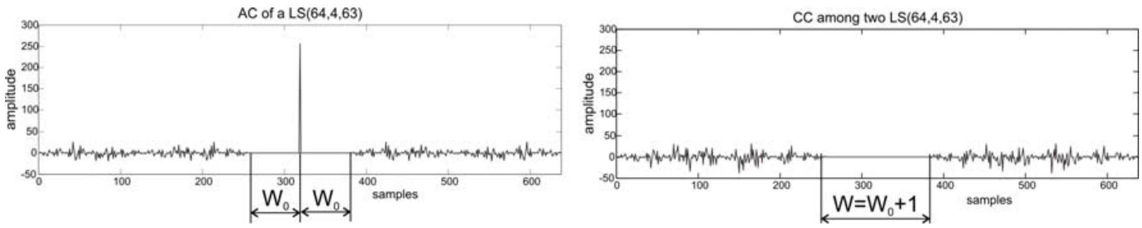
Fig. 2 shows the correlation properties for the case of Kasami sequences with length 255 bits (a); of interleaved CSS sequences with length 256 bits and generated from sets of four complementary pairs (b); and of LS(64,4,63), that is, of LS sequences with length 319 bits and an IFW of 129 bits (c). For each family of sequences, those who have the better performance in case of four simultaneous users have been chosen. Notice that the AC peak of Kasami and interleaved CSS is equal to their length, but the AC peak of LS sequences it is equal to $K•N$.



a) AC and CC functions for Kasami sequences with length 255 bits.



b) AC and CC functions for Kasami sequences with length 255 bits.



c) AC and CC functions for LS(64,4,63).

Figure 2.- Correlation functions for Kasami, M-CSS and LS codes.

LOCAL POSITIONING SYSTEM

Some simulations have been achieved to evaluate the feasibility of the previous codes in a LPS. The system is composed by a group of five beacons, which can be codified with Kasami, M-CSS or LS codes. These codes have been BPSK modulated by using a symbol with one period of a 50KHz square signal. The five beacons are placed over the floor with a height of 3m, and into a 1m x 1m surface, whereas the robot has been located at the coordinates (x=0.2m, y=0.1m, z=0.3m), as can be seen in Fig. 3. All the beacons are synchronized by a common clock and they periodically emit their corresponding code every 50ms. The emissions are digitalized with a sampling frequency of 500 kHz, demodulated and the corresponding correlations are carried out. A signal-to-noise ratio of SNR= 0dB has been assumed.

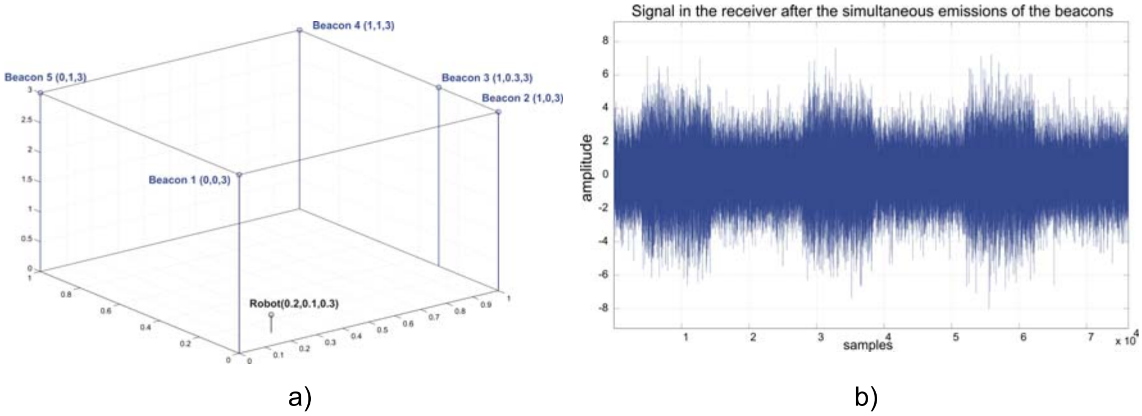


Figure 3.- a) Scheme of the beacons distribution. b) Kasami signals received with a SNR=0dB.

Firstly, the beacons are encoded with five pseudo-orthogonal Kasami codes with length 1023 bits, thus the duration of the signals is 1023•20µs=20.46ms. Fig. 4.a) depicts the correlator output for the emission from beacon 2. The maximum values indicating the TOAs of every emission can be clearly observed. A similar detection has been carried out with interleaved 32-CSS (the final length of the emitted macro-sequence is of 1024 bits). Fig. 5 shows the correlation results from beacon 2.

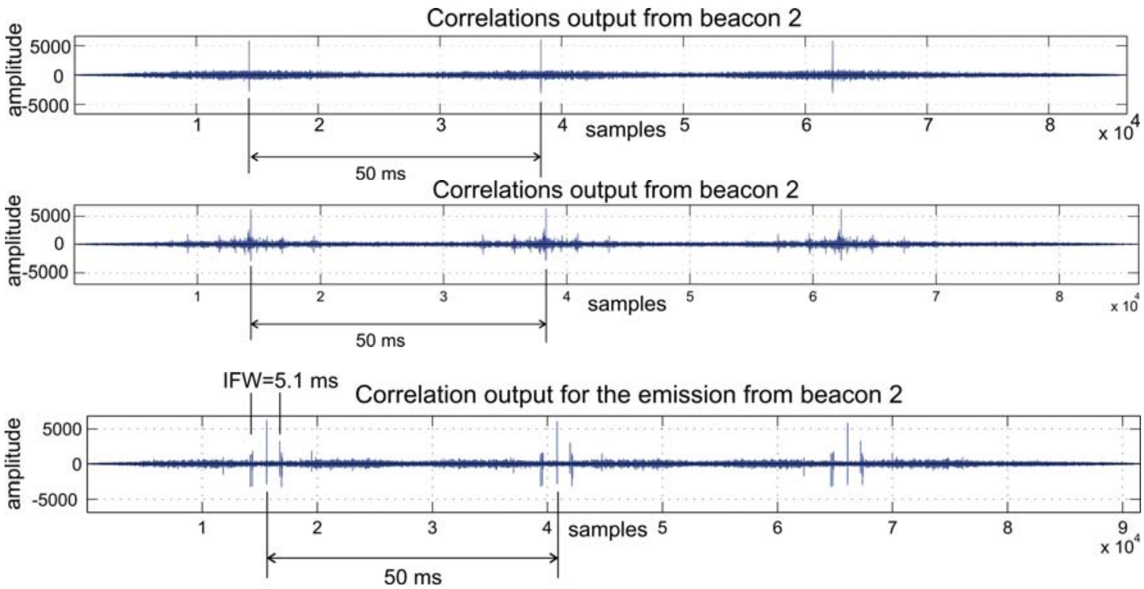


Figure 4.- Correlation output from beacon 2, in case of a SNR=0dB: a) 1023-Kasami codes, b) Macro-sequence from 32-CSS and c) LS(128,8,127).

Finally, every beacon has been encoded with a LS(128,8,127): a 1151-bit LS code with an IFW of 255 bits. Thus, the duration of the signal is 23.02ms, and the maximum delay among the arrival of the diferent emissions is T_{dmax}=127•20µs=2.54ms. Fig. 4.c) depicts the output of correlator 2, where the IFW can be observed.

CONCLUSIONS

A local positioning system based on the use of Kasami, interleaved M-CSS and LS sequences has been presented. It consists of using simultaneous emission from ultrasonic beacons. Every beacon is encoded with a particular sequence.

The differences between sequences have been pointed out: all of them perform very well in asynchronous detection. Kasami and interleaved M-CSS have good properties in all theirs autocorrelation and crosscorrelation functions. On the other hand LS codes have the particularity of having a perfect auto-correlation and cross-correlation functions in the IFW.

The mobile receiver does not require knowing the emission instant, and therefore, there 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.

It is important to remark that interleaved M-CSS and LS codes admit the use of efficient correlators, and then real-time operation is easier to be achieved.

Finally, the performance of the system has been tested by simulation.

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