A COMPARATIVE ANALYSIS OF TWO MODULATION SCHEMES FOR THE EFFICIENT TRANSMISSION OF COMPLEMENTARY SEQUENCES IN A PULSE COMPRESSION ULTRASONIC SYSTEM

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Abstract

Pulse compression techniques have been widely used in ultrasonic systems that require high precision time-of-flight measurements or have to work in environments where the physical restrictions lead to poor signal-to-noise ratios. Different types of codes with good auto-correlation and cross-correlation properties are employed in the signal processing of these systems and, among them, complementary sets of sequences represent a novel solution which notably improves the systems performance. In this paper two modulation schemes are presented for the efficient transmission of complementary sets of four sequences through the narrow bandwidth which characterizes ultrasonic transducers.

Keywords
Pulse compression, ultrasonic systems, complementary sequences, modulation.

1. INTRODUCTION

Throughout the last two decades, many systems based on the time-of-fight (TOF) measurement of an ultrasonic pulse have incorporated signal processing techniques borrowed from radar theory. These systems are characterized by a notably improved time precision and spatial resolution, and they can operate in environments with very poor signal-to-noise ratios at the expense of increasing the computational complexity of the signal processing tasks. Most of these systems have also the ability to discern between many signals emitted simultaneously thanks to their signal coding, a property which eliminates the crosstalk problem increasing the system performance.

Recently, a new encoding scheme based on complementary sets of four sequences, has been proposed by the authors for an ultrasonic obstacle detection system [1]. A general description of this system is given in section 2, where the problems that lead to the need of developing new modulation schemes for these signals are also shown. Two modulation schemes are presented and compared in sections 3 and 4. Section 5 shows the results of the experimental analysis carried out with this schemes and finally the conclusions are outlined in section 6.

2. DESCRIPTION OF THE SYSTEM

Complementary sets of sequences are a generalization of Golay pairs which may contain more than two sequences [2]. A set of N binary sequences whose elements are either +1 or – 1 is said to be a complementary set if the sum of their aperiodic auto-correlation functions equals zero for all nonzero time-shifts. If $\{a_1, a_2, \ldots, a_N\}$ is a set of N sequences with length L, and R_{xx} represents the auto-correlation function of the sequence $x[i]$ then:

$$R_{a1a1}[i] + R_{a2a2}[i] + \cdots + R_{aNaN}[i] = \begin{cases} N \cdot L, & i = 0 \\ 0, & i \neq 0 \end{cases} \qquad (1)$$

The main advantage of using complementary sets of sequences is that it is possible to generate more than two mutually orthogonal sets with ideal null cross-correlation properties. In particular, for the case $N = 4$, the sets $A = (a_1, a_2, a_3, a_4)$, $B = (b_1, b_2, b_3, b_4)$, $C = (c_1, c_2, c_3, c_4)$ and $D = (d_1, d_2, d_3, d_4)$ are mutually orthogonal when:

$$R_{x1y1}[i]+R_{x2y2}[i]+R_{x3y3}[i]+R_{x4y4}[i]=0 \qquad (2)$$
$$\forall i \quad \forall\ x,y\in\{a,b,c,d\} \qquad x\neq y$$

The block diagram of a generic sensorial system based on the emission of these sets is shown in Figure 1. This system has one emitter/receiver pair for each one of the four sets to be transmitted. At each receiver, the input signal is correlated with the four sequences constituting the corresponding set, and the results of these correlations are added in order to obtain the peak values predicted by Eq. (1). All the sets can be transmitted simultaneously without affecting the detection process by virtue of their orthogonality.

The correlations are carried out by the *Efficient Sets of Sequences Correlator* [3], a digital filter that performs the correlation of a L-bits length sequence with only $4\cdot\log_2 L$ operations, instead of the $2\cdot L-1$ needed by the straightforward correlator,.

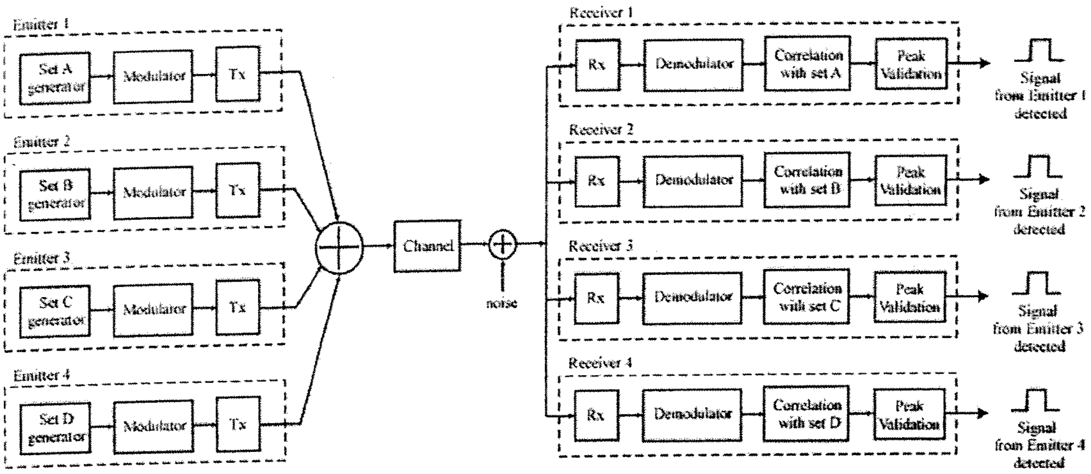


Fig. 1. Block diagram of a generic sensorial system based on the emission of four complementary sets of sequences (A, B, C and D).

In an ultrasonic system, the transducers employed to transmit (Tx) and receive (Rx) the encoded signals have band-pass characteristics with a narrow bandwidth, and the binary sequences have to be modulated in order to shift their spectra to the region of maximum response of these transducers. A simple solution, many times encountered in the literature, is a BPSK modulation that employs one or more periods of the carrier as modulation symbol. The only disadvantage of this modulation scheme is that it is necessary to transmit at least one period of the carrier for each bit in the sequence.

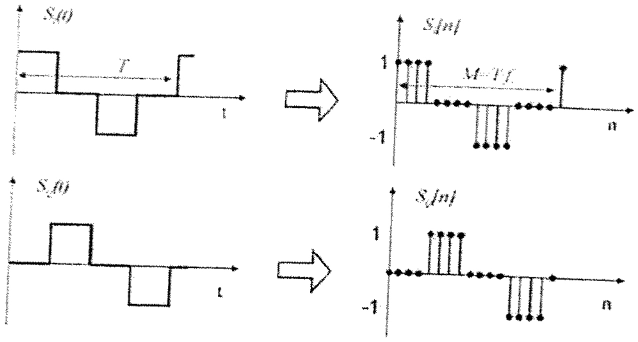
When dealing with complementary sets of four sequences, every emitter has to transmit the four sequences contained in its corresponding set, and a BPSK modulation would require at least $4\cdot L$ periods of the carrier to transmit the whole set of sequences with length L. This transmission time can be a critical parameter in systems where the conditions change so rapidly that they will not be the same throughout the emission period, a fact that strongly deteriorates the results of the correlation processes. A mobile robot or a system intended for outdoors operation are typical examples of these kinds of systems.

3. DIGITAL QPSK MODULATION

Digital QPSK has been already used to simultaneously transmit the two sequences contained a Golay pair [4]. This modulation is based on the two orthogonal symbols shown in Figure 2a, which can be viewed as discrete versions of a cosine (in-phase symbol) and a sine (in-quadrature symbol). Figure 2b shows these symbols when they are sampled with a sampling rate 16 times higher than the frequency of the carrier.

$$S_I(t) = \begin{cases} 1 & \text{if } \cos(\omega_o t - \pi/4) \geq \cos(\pi/4) \\ -1 & \text{if } \cos(\omega_o t - \pi/4) \leq \cos(3\pi/4) \\ 0 & \text{Otherwise} \end{cases}$$

$$S_Q(t) = S_I\left(t - \frac{T}{4}\right)$$



(a) (b)

Fig. 2. QPSK modulation: (a) Symbols in-phase and in-quadrature, (b) Discrete-time versions of these symbols

This modulation scheme can also be used to transmit sets of four sequences reducing to half the total time required by a BPSK modulation. The modulation process can be described in two steps:

1. The four sequences in a set are multiplexed generating this way a new sequence with 4·L bits.

$$\left.\begin{array}{l} x_1 = [x_{11} \quad x_{12} \quad \cdots \quad x_{1L}] \\ x_2 = [x_{21} \quad x_{22} \quad \cdots \quad x_{2L}] \\ x_3 = [x_{31} \quad x_{32} \quad \cdots \quad x_{3L}] \\ x_4 = [x_{41} \quad x_{42} \quad \cdots \quad x_{4L}] \end{array}\right\} \Rightarrow x = [x_{11} \quad x_{21} \quad x_{31} \quad x_{41} \quad \cdots \quad x_{1L} \quad x_{2L} \quad x_{3L} \quad x_{4L}] \quad (3)$$

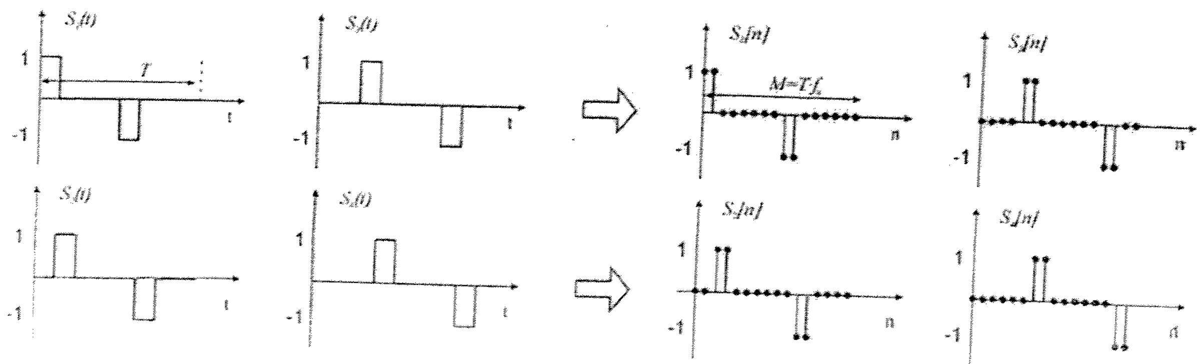
2. The bits of the new sequence are grouped in pairs (x_{1i}, x_{2i}), (x_{3i}, x_{4i}), and each pair is combined with the symbols S_I and S_Q to generate two signals (16 samples each) defined as follows:

$$S_{x_{1i}x_{2j}}[n] = x_{1i} \cdot S_I[n] + x_{2j} \cdot S_Q[n] \qquad S_{x_{3i}x_{4j}}[n] = x_{3i} \cdot S_I[n] + x_{4j} \cdot S_Q[n] \quad (4)$$

With this procedure, each pair of bits from sequences *a* and *b* is transmitted in one cycle of the carrier, and each pair from *c* and *d* in the following one, giving a total of *2L* cycles for the whole transmission.

4. FOUR DIMENSIONAL MODULATION

A new modulation scheme has been developed with the aim of reducing even more the time required for the simultaneous transmission of the four sequences in a set. This scheme is based on the four orthogonal symbols shown in Figure 3a, and reduces to one quarter the time required by a BPSK modulation. Figure 3b shows the discrete-time versions of these symbols, assuming again a sampling rate 16 times higher than the frequency of the carrier.



(a) (b)

Fig. 3. Four dimensional modulation: (a) Orthogonal symbols, (b) Discrete-time version of these symbols

The modulation process is very similar to that of the QPSK modulation:

1. The four sequences in a set are multiplexed generating this way a new sequence with $4 \cdot L$ bits (Eq. 3).
2. The bits of the new sequence are grouped in quartets (x_{1i}, x_{2i}, x_{3i}, x_{4i}), and each quartet is combined with the orthogonal symbols shown above to generate a 16 samples signal defined as follows:

$$S_{x_{1i}x_{2i}x_{3i}x_{4i}}[n] = x_{1i} \cdot S_1[n] + x_{2i} \cdot S_2[n] + x_{3i} \cdot S_3[n] + x_{4i} \cdot S_4[n] \quad (5)$$

In this case, it is necessary only one cycle of the carrier to transmit four bits, one from each sequence. There is a price to pay for this improvement in the emission time, though. The four dimensional (4D) modulation spreads more energy all over the spectrum than the BPSK and QPSK modulations, which have very similar spectral characteristics (see Figure 4). This effect should be translated into a decrease in the SNR obtained with the new modulation.

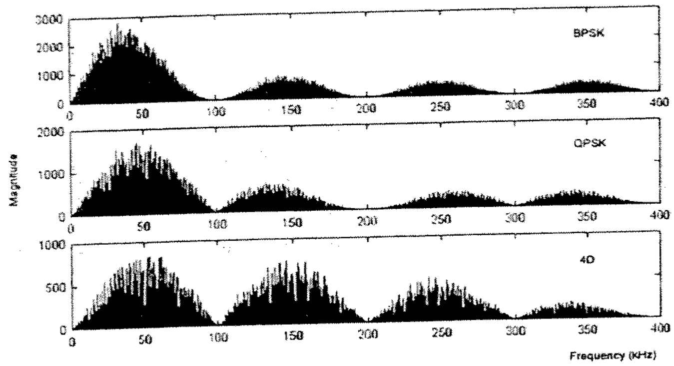


Fig. 4. Spectral magnitude characteristic of the modulation schemes.

5. EXPERIMENTAL RESULTS

The modulation schemes described in the previous sections have been experimentally tested with the help of the equipment shown in Figure 5. This equipment consists of two electrostatic transducers, a high frequency microphone with an amplifier, and a PC provided with a data acquisition card to generate and acquire the modulated signals. The system accomplishes the simultaneous emission of two mutually orthogonal sets of four sequences with the possibility of selecting the length of the sequences (64, 256, 1024 or 4096), and the type of modulation (BPSK, QPSK or 4D).

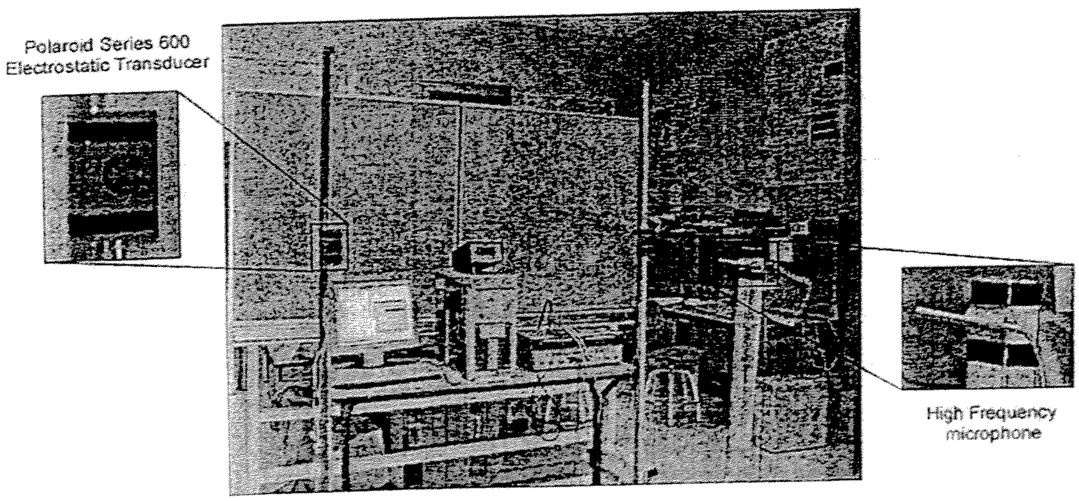


Fig. 5. Equipment and experimental setup.

The experimental results of the detection process described in Figure 1 are shown in Figure 6 for the particular case of two orthogonal sets with sequences of 256 bits. The carrier frequency is 50 kHz and the sampling rate is 800 kHz (16x50). As can be seen in this figure, the signal-to-noise ratios are very similar in all cases, owing to the fact that the noise in this figure is not external noise but self-induced noise caused by the incoherent demodulation of the signals. The detection periods are related as expected.

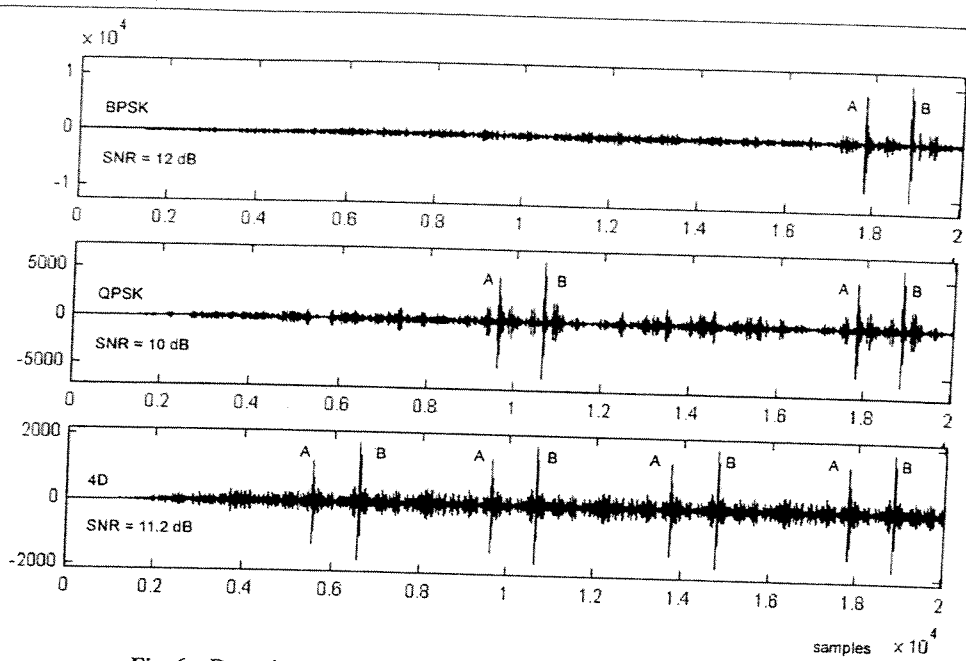


Fig. 6. Detection process of two orthogonal sets for different modulations.

6. CONCLUSIONS

In this paper two modulation schemes have been proposed for the simultaneous emission of complementary sets of four sequences through ultrasonic transducers. Both schemes decrease the transmission time required by a classical BPSK modulation, and all of them seem to suffer from the same levels of self-induced noise. The signal-to-noise ratios achieved in the output signals are very similar in all cases, despite the spreading of energy in the spectrum caused by the 4-D modulation.

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