Ultrasound modulation and codification for localization systems

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Abstract

This paper aims to serve as a short introduction to the advantages that can be obtained by applying modulation and codification techniques in many processes involving ultrasonic signals, and specifically, in the localization systems designed and built at the Institute for Industrial Automation. We will consider digital modulation of the ultrasonic signals, useful pseudo-random sequences for codification, transducer technologies and the expected theoretical benefits from the process. Some of these features will be demonstrated with experimental tests.

1. INTRODUCTION

Ultrasonic sonar has long been one of the key technologies used in Robotics for localization and environment exploration. Its key features are well known: good range resolution, ruggedness, simplicity and small processing demands; among its disadvantages we can list the slow update rate, the difficulty to interpret the information provided by complex environments, and the interference or crosstalk when several transducers operate simultaneously.

A typical ultrasound-based system for localization of an autonomous vehicle is illustrated in figure 1. A set of ultrasonic transmitters or beacons placed at known locations are periodically sending pulses which are picked by two receivers (A and B) on board of a mobile vehicle. A processing platform on the vehicle computes the times-of-flight (TOFs) of the ultrasonic signals (synchronization is achieved through a radio link), and by triangulation finds its own position and orientation. Determination of three coordinates (x, y, θ) requires the measurement of the TOFs from at least two beacons, although a robust system will commonly redundant beacons to provide some degree of outlier rejection, and verify the position measurement integrity.

In the simplest scheme, the beacons are fired sequentially (at times t_i, t_{i+1}, etc), allowing enough time

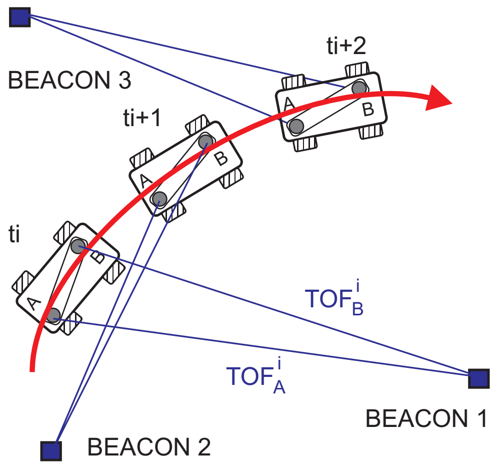


Figure 1: Tracking of a mobile vehicle with an ultrasonic positioning system.

for travelling and proper attenuation of the ultrasonic signal between consecutive emissions. However, at the relatively slow propagation speed of ultrasound in air, the vehicle's coordinates will have changed during the completion of an emission cycle. As a result, it is not clear *which* vehicle's position we are computing through measurements $\{\text{TOF}_\text{A}^i, \text{TOF}_\text{B}^i, \text{TOF}_\text{A}^{i+1}, \text{TOF}_\text{B}^{i+1}, \ldots\}$. There are ways to incorporate this difficulty into the position estimation algorithm (using, for example, a Kalman filter), but it would be much more convenient if we could collect all the ranges from the beacons at the same time.

Concluding, it is clear that in this particular localization system, the simultaneous operation of all transmitters would increase the measurement update rate, in principle by a factor equal to the number of beacons, if we neglect the processing time. An added benefit is that the radio link used for synchronization with the mobile vehicle could be suppressed and the pseudoranges (time differences instead of absolute times) to the beacons could be used for triangulation, in the same fashion as the GPS does [1].

2. CDMA BASIC THEORY

If a communications engineer was to consider the problem stated in the introduction, she would speak of a situation of multiple access (MA) to a channel (the ultrasonic signals propagating through the air) by several users (the beacons). A well known example of MA is a mobile telephony cell, with several users speaking to and communicating with the base station simultaneously.

There are three basic schemes for multiple access:

- Time division multiple access (TDMA), in which the users take turns to emit and receive their signals; this is essentially the scheme described in the introduction.
- Frequency division multiple access (FDMA), in which the users are allocated different frequency bands which they use simultaneously, as in conventional radio. This is very difficult to implement with ultrasonic signals because current air transducer technology does not offer enough bandwidth to accommodate more than perhaps one or two users (see section 5). In principle one could use a set of physically different transducers, each tuned to a given frequency, and assigned to a given user. Although this approach would probably work, it is inelegant and difficult to set up, considering the different physical parameters (impedance, sensibility, emitting pattern, attenuation, etc) of each transducer.
- Code division multiple access (CDMA) in which the users emit simultaneously and share the same frequency band, but are assigned different codes which can be processed to uniquely identify them. This involves the use of digital modulation technologies to imprint an identification code onto the signal transmitted by each transducer.

Details of the modulation and codification processes are offered next.

2.1. Digital modulation schemes

Digital modulation serves to translate a bit message from the baseband into the passband of the transducer, and is usually achieved by manipulating the amplitude, the frequency or the phase of a carrier signal at a proper frequency [2].

Phase modulation (PSK) is the most common way of digitally modulating an ultrasonic air signal [1]. PSK consists in encoding the transmitted message (a sequence of bits $g[n]$) into the phase $\phi(t)$ of the carrier signal:

$$s(t) = \sin(2\pi f_0 t + \phi(t)), \quad (1)$$

where a single bit takes n_{cyc} cycles of the carrier. In the case of binary PSK (or BPSK), the phase shifts between $\phi(t) = 0$ if $g[n] = -1$ and $\phi(t) = \pi$ if $g[n] = 1$. We will adopt the convention of taking -1 and +1 as possible bit values, instead of 0 and 1.

2.2. Codification schemes. Pseudo-random sequences

In CDMA communications, each user i is assigned a N_b bits long binary code $g_i[n]$, which is modulated as described above and transmitted into the medium. As all users can emit simultaneously and share the bandwidth, the ability to isolate a given user depends on two principles: (a) that there is a way to process a signal and detect a given code (the correlation operator); and (b) that codes can be built that have minimum mutual interference (code orthogonality). Mathematically we can write these desirable properties of a set of digital codes $\{g_i[n]\}$ as:

$$\begin{aligned} R_{ii}[m] &= \sum_n g_i[n] g_i[n+m] = \delta[m] \\ R_{ij}[m] &= \sum_n g_i[n] g_j[n+m] = 0, \end{aligned} \quad (2)$$

where $R_{ij}[m]$ is the correlation of codes i and j and $\delta[m]$ is Kronecker's delta. The first condition states that correlating a code with itself will give a peak placed at the true lag (corresponding to the echo's arrival time) and a zero value elsewhere; the second that the codes are perfectly orthogonal and the influence of any number of them can be exactly eliminated. Mathematically, white noise signals uncorrelated to each other would verify the set of equations 2; as this is not a practical approach, digital codes which resemble white noise (but are otherwise completely deterministic) are used instead—that's the reason why these signals are called pseudo-random codes.

Unfortunately, no set of codes can be built that satisfy exactly the conditions above, a fact which has spanned several code families with different characteristics. We will enumerate only the most popular in the literature[2]. Maximum length sequences have optimum autocorrelation but far from optimal cross-correlation properties. Hadamard-Walsh codes fulfill exactly the conditions given in equation 2, but only in the case of synchronicity ($m = 0$), which makes them useful in mobile telephony but not in ultrasonic applications where the time of flight is a priori unknown. Golay codes have long been favored by the ultrasonic community; they fulfill *exactly* the condi-

[1] Amplitude modulation (ASK) is found in the ultrasonic ranger reported in [3]. A simple two-bit FSK signal used for time delay estimation is described in [4]. Full FSK ultrasonic coding is used in the Hexamite positioning system (`http://www.hexamite.com`).

[2] The study and construction of orthogonal codes is an area of active research, linked to the field of commutative algebra.

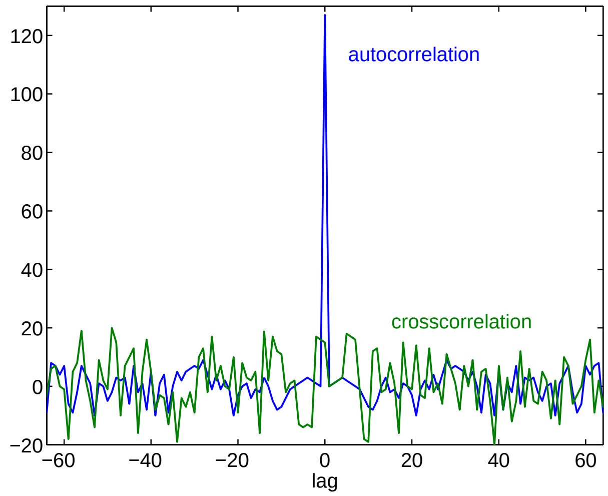


Figure 2: Autocorrelation (blue) and cross-correlation (green) of two 127 bits long Gold codes.

tions in equation 2 if used in pairs, requiring quadriphase (QPSK) modulation to encode the two-bit symbol. A limitation of Golay codes is that there is only one pair of sequences which is perfectly orthogonal to a given Golay pair, so only two users could be accommodated with them; the workaround consists in employing complementary (sets of more than two sequences modulated at the same time) or polyphase sequences. An advantage of Golay sequences is that efficient (in the sense of required number of operations) correlators exist for them, a fact which has been considered by the group of Ureña and coworkers [5] to design sensor units and dedicated hardware that exploit these complexity reduction properties.

Finally, Gold codes are a good approximation to equations 2, providing a high auto-correlation peak and bounded cross-correlation properties; these are the codes of choice for the GPS positioning system. Their properties approach the ideal results when the number of bits (N_b) grows. In figure 2 we show the correlation properties of the length 127 codes that will be used later in this paper. The small peaks around the maximum are sometimes called sidelobes in the literature (not to be mistaken with the angular sidelobes of ultrasonic transducers).

2.3. Processing of the received signal

The advantages of CDMA schemes are achieved through signal processing. A schematic vision of a CDMA receiver is shown in figure 3.

Part (a) of figure 3 shows the demodulator stage. It is a common practice in carrier modulation schemes to shift the signal down to an intermediate frequency or to the baseband (near 0 Hz) before further processing. Due to the relatively low carrier frequencies used in ultrasonic air applications, most processing systems can handle signals in the passband right away, so this step would not be strictly required. However, it will be followed in this paper, and we will use the standard inphase-quadrature (IQ) demodulator to construct the complex envelope $r(t) = r_I(t) + jr_Q(t)$ from the incoming signal $s(t)$. The continuous signal $r(t)$ is sampled at the bit intervals[3] to produce the discrete signal: $r[n] = r(nT_b)$.

Detection of each individual user is achieved with the correlator bank of part (b) of figure 3. It consists in a set of filters matched to the codes $\{g_i[n]\}$, producing the following outputs:

$$y_i[m] = \sum_n r[n]g_i[n+m]. \tag{3}$$

A peak detector finds the time of arrival TOF_i and amplitude A_i of the signal from the ith transducer.

2.4. Alternatives to digital modulation

To conclude this section, we would like to comment that CDMA schemes, which are based in digital modulation of the ultrasonic signals, are not the only way to achieve good resolution, low crosstalk and extract rich information of the environment. Other alternatives exist, whose common feature seems to be the full exploitation of the bandwidth that is available. One example is the sonar system described in [6], that uses pseudo random noise signals created to match the transducer's bandwidth.

The chirp (a linearly modulated frequency sweep) has long been used for pulse compression in sonar and medical ultrasound [7]. Bats, which use ultrasound for navigating and hunting, produce signals which are a combination of modulated frequency and constant frequency (in order to use the information from the Doppler shift of the returned echo), and also employ the higher harmonics of the base signal, spanning a typical range from 20 to 120 kHz. Evolution has fine-tuned the ultrasonic echolocalization system of bats to an amazing degree of complexity, enabling them to build a three dimensional map of the surrounding environment, with potential resolution of millimeters, and use it for navigation and hunting in cluttered environments [8]. This is beyond the capacity of any man made ultrasound system built yet.

3. ADVANTAGES OF SIGNAL MODULATION AND CODIFICATION

In this section we will describe the benefits that can be obtained from the processes of modulation and codification of ultrasonic signals.

[3]Signal synchronization is a tricky issue which we do not have space to deal with properly here. We will consider it again in the experiment of section 6.3.

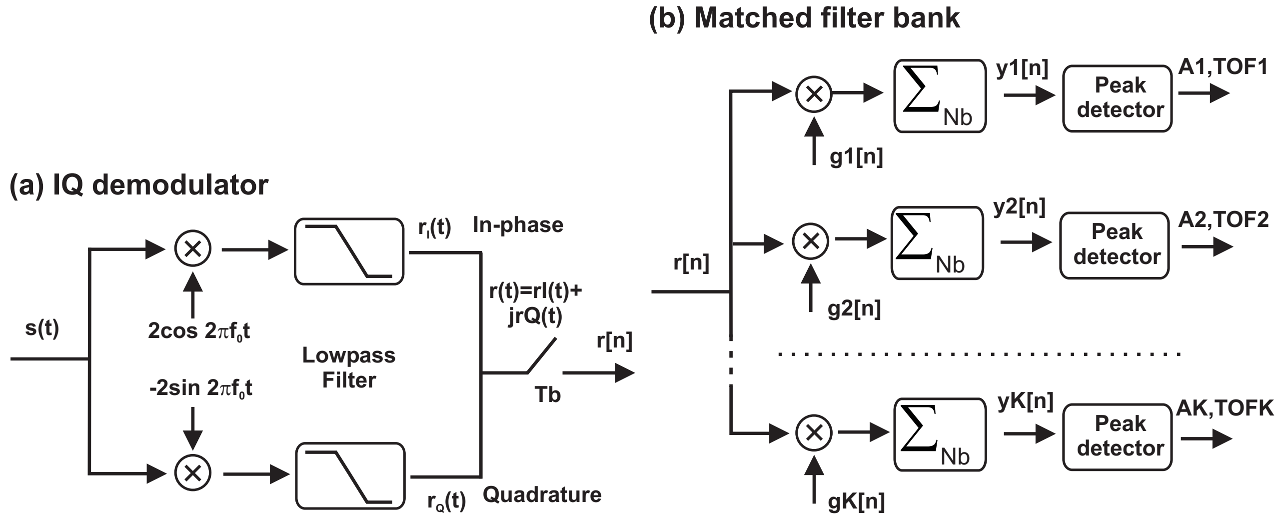


Figure 3: Processing stages of a CDMA system: (a) Inphase-quadrature (IQ) demodulator used to compute the complex envelope or baseband representation of the ultrasonic signal; (b) Correlator bank to detect the different users.

3.1. Simultaneous operation of several transducers

Notably, the capacity of CDMA to accommodate several users simultaneously makes it a very useful technique in communication systems. Ultimately the capacity of a CDMA system is limited by the multiple access interference (MAI) between users, a problem which is documented in the literature from mobile telephony [9]. Algorithms for MAI mitigation exist, with significant improvement at the expense of more intense signal processing.

As a by-product, CDMA also provides system resistance to multipath propagation, which is ubiquitous in indoor ultrasonic applications, since most objects reflect sound waves specularly. Multipath propagation can be viewed as a multiuser problem (in this case, self-interference) and partially rejected with CDMA techniques.

3.2. Enhanced precision in estimation processes

In robot navigation an ultrasonic signal is emitted into the air to detect the presence and position of obstacles in its way. In medical elastography an ultrasonic signal is sent into the human body to determine the thickness of a muscular tissue. These two applications are examples of *estimation* processes. The accuracy of the obtained results (range to a target, tissue thickness) depends on the characteristics of the signal and the environment, and is quantified mathematically by the so-called lower bounds [10]. One well studied example is the determination of the TOF (or range) to a target (see figure 1); it can be proven that for a coherent process (i.e., one which includes the information of the phase) and with a sufficiently high SNR, the variance of the measurement is given by the Cramér-Rao criterion, which numerically amounts to [11]:

$$\sigma^2_{\mathrm{TOF}} \geq \frac{1}{16\pi^2 BT f_0^2 \mathrm{SNR}}. \tag{4}$$

From this equation we see that several factors contribute to obtain higher precision. The first is the central frequency f_0, which however is limited by the increasing attenuation of ultrasonic propagation in air with high frequencies. Increasing the SNR is also beneficial to decrease the measurement error; however the transducers used, the measurement range, etc, set a limit for the signal amplitude that can be obtained (besides, in medical applications, health regulations dictate the maximum peak power which is allowed in an ultrasonic test). The last factor that we can manipulate is the product of the signal bandwidth and duration (or BT product for short). For waveforms of the kind envelope times carrier this product is limited (essentially equal to one), but it can be increased without bounds if we use chirps or coded waveforms, which are referred to as long BT signals, or pulse compression waveforms. Therefore, use of coded waveforms leads to a more accurate determination of parameters in an estimation process.

3.3. Processing gain

Processing gain can be defined as the signal gain which is obtainable by taking advantage of the signal's structure—in essence it could be described as a smart averaging with the correlation operator. Numerically it can be shown that this gain is given by:

$$\mathrm{PG} = 20 \log_{10} N_b \qquad \text{in dB},$$

where N_b is the number of bits of the encoded signal. Processing gain is really another way of looking at the precision enhancement mentioned above. The main benefits of processing gain are the capacity to detect low amplitude signals (even below noise level) and the resistance to interference from noise sources and other users. Processing gain is obtained at the expense of increased processing requirements (time and storage capacity), and may pose a limit to systems operating in real time.

3.4. Data transmission

The ultrasonic channel can also be used for digital data transmission among two points with line of visibility, with a speed dictated by the available bandwidth and SNR. A possible application would be to replace the radio links used for data transmission in some systems. We'll show how ultrasonic communication is feasible in section 6.3.

4. APPLICATIONS

In this section we list some of the applications of modulation and codification of ultrasound.

4.1. Localization systems

As stated in the introduction, our motivation for coded excitation of ultrasound comes from the development of localization systems, and is inspired by the very successful GPS system. Our group is currently developing a positioning system to automatize the job of archaeologists working in the findings in Gran Dolina, in Atapuerca (Spain), where human remainings from about 800000 years ago have been found, which could correspond to the first European inhabitants (*Homo antecessor*).

The task of the archaeologist consists in recovering all the different pieces (bones, glass, ceramics, etc) found in the place and noting down their positions; later all the data is used to recreate the original arrangement of the settlement. The process of localization of the pieces starts with a division of the area with strings to form a reticule, and measuring manually (with a tape) and writing the coordinates of the found pieces with respect to this reticule (see figure 4, left). This method is obviously slow and prone to human errors.

The system developed at IAI [12] is shown in the right part of figure 4, and consists of two parts: an array of ultrasonic transducers, placed at fixed positions in a framework above the work area, and a set of sticks operated by the archaeologists. Each stick holds an ultrasonic transducer on its top and another in its middle point; when the user points the tip of the stick at the object to be positioned, and presses a button in the stick, an ultrasonic transmission is initiated from the stick to the static transducer network. Measurement of the times-of-flight and triangulation permits to find the position of the emitter transducers, and, from them, the coordinates of the tip. These coordinates are transmitted by a radio link to a remote computer which keeps a log on the different findings. CDMA codification of the ultrasonic signals is required because: (a) several users might be sharing the workspace; (b) we contemplate bidirectional transmission (i.e., also down from the framework transducers to the sticks) in order to mitigate the effects of the wind on the propagation of ultrasound. The first trials with a prototype system have given accuracies in the millimeter range, which are demanded in this kind of application.

4.2. SLAM

Simultaneous Location and Mapping (SLAM) is the use of sonar ultrasonic signals by a robot to locate obstacles in its path and dynamically build a map of its environment. To cover as wide an area as possible, robots are equipped with many transducers (for example, the venerable B-21 from RWI has a ring of 24 capacitive sensors around its body), which causes the aforementioned problems of crosstalk between emitters, and difficulty to identify the origin of the received echoes. Systems reported in the literature employ time scheduled sensor firings (i.e. TDMA) and use either the number of pulses in each emission [13] or the time separation between consecutive emissions [14] to uniquely identify the emitting transducer. It is clear that CDMA schemes are potentially more efficient than these methods.

Another quite interesting research line concentrates in extracting more information from the environment than merely the range and bearing to the nearest obstacle provided by conventional sonars. In 1987 Kuc published a classic paper [15] in which he demonstrated that the combination of the arrival times of ultrasonic echoes at several transducers and the physics of wave reflection, could be used to classify the reflectors into three simple categories: flat walls, edges and corners. Starting with these templates as basic units permits to build more accurate environment maps, a very useful fact for SLAM applications. Following this result, Peremans and Audenaert [16, 17] built a tri-aural (one transmitter and three receivers, or 1T/3R) structure which used a BPSK modulated, 13 bit long Barker code signal. The sensor was able to discriminate objects as close as 2 cm, as well as correctly classify multiple reflectors into the three categories described above in rather complex environments. This line of work was further extended by Jorg [6], with a sensor with two emitters and two receivers (2T/2R), and pseudo-random signals, using a matched filter for processing the received echoes. More recently, the group of Ureña [18] at the Universidad de Alcalá used a two emitter and four receivers structure (2T/4R), as shown in figure 5 and Golay complementary pair sequences for each transmitter, modulated with QPSK. His group has made use of the so called efficient Golay correlators (see section 2.2) to optimize the signal processing time. The use of custom designed FPGA hardware permits real time operation with long signals (up to 128 bits), as was demonstrated in experimental trials on board of a CyCab vehicle (see

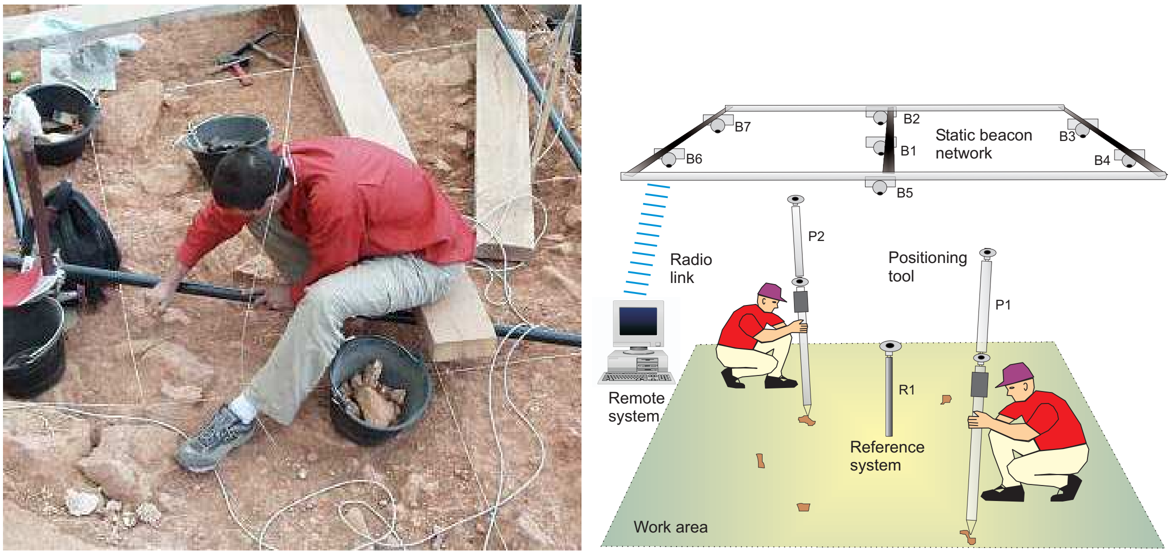


Figure 4: Manual positioning of pieces in archaeological findings and the system developed at the IAI for assistance and automatization of the task.

Figure 5: Four transducers (2T/4R) sensor structure employed at the Universidad de Alcalá, and its application for SLAM in a CyCab vehicle.

figure 5) [5].

4.3. Other applications

For the sake of completeness we mention other areas where codification and modulation of ultrasonic signals have found application.

Sonar (and radar) were the first fields to exploit the advantages of coded signals, with all the basic concepts (long *BT* signals, matched filter, ambiguity functions, etc) being established during and after the Second World War.

Medical ultrasound is a big field of application of coded excitation today [19]. Activity on this topic began in the early 80s, with several researchers pointing how improvements in penetration depth and obtainable resolution could be gained from signal codification; around that time Lee [20] proposed the use of Golay sequences to permit multi-mode (several directions simultaneously) operation of phased arrays for scanning. Progress in the area was slowed down by the difficulty in analyzing the propagation of ultrasound in the human body (which adds complications like frequency dependent tissue attenuation and the presence of speckle) and the inexistence of transducers with adequate bandwidth. However this field has experimented phenomenal advances in the last five years; one needs only to see the spectacular quality of today's echographies, which can be attributed, among other factors, to the increased performance obtained with coded signals [21].

Finally, other fields which benefit from ultrasonic codification are non-destructive testing and non-contact ultrasonic imaging, as the system for study of wood samples described in [22].

5. TRANSDUCTION TECHNOLOGIES

Unlike the case of electromagnetic signals, where huge bandwidths are readily available for codification and modulation, ultrasonic systems in air are much more restricted by the transducer technology available and physical constraints, like the high difference of acoustic impedances between transducer materials and air and the attenuation of the signal at high frequencies. The net result is relatively low transducer bandwidth and sensibility [23].

Piezoelectric transducers are resonant devices with a high quality factor and correspondly low bandwidth (typically 2 kHz for a 40 kHz central frequency); they are commonly used in pulse-echo air applications, without codification. Several methods have been developed for damping the resonance and increasing the bandwidth, like the careful use of backing layers. Piezopolymer (PVDF) transducers show higher bandwidth (in the order of 8–10 kHz), due to their reduced acoustic impedance (closer to that of air). Of the commonly available transducers, the capacitive ones have the highest bandwidth (about 30 kHz for some Polaroid models), and they are the ones usually employed for modulation and codification [17, 6, 18].

More recently arrived technologies show the promise of combining high SNR and bandwidth, although for the moment they are not available as off-the-shelf components. Multifrequency piezocomposites are piezoelectric ceramic rods of different thicknesses embedded in an inert polymer matrix, which have a bandwidth controllable by design [24]. The capacitive micromachined ultrasonic transducers (CMUTs) are small capacitors fabricated with CMOS technology, with a remarkable capability for array fabrication and relative large bandwidths (for example, in [25], a bandwidth of 600 kHz and a central frequency of 1.2 MHz are reported). Recently introduced, the electromechanical film (EMFi) is a polypropylene film which holds a permanent charge and therefore acts like an electret [26]. These transducers have found their first application in the ultrasonic field as general broadband transducers in the Circe project[4], where a usable frequency range of 20–200 kHz has been reported.

6. EXPERIMENTAL TESTS

We will clarify some of the features of the signal codification and modulation with the experimental setup shown in figure 6. The system consists in a PC connected through the GPIB bus to an Agilent's 33120A arbitrary waveform generator which is used to create the coded waveforms. The signals are emitted and received with a couple of Prowave's 400WB16 'wideband' piezoelectric transducers, placed 1 m apart. They have a quoted bandwidth of 15 kHz, which is achieved by damping the piezo disk with silicone (this design also causes a drop of amplitude of about 23 dB with respect to the resonant version of the same transducers). The received echo is amplified with a Bruel&Kjaer 5935 amplifier (adjustable gain from 0 to 50 dB) and captured with an Adlink PCI-9812 acquisition card (the sampling frequency is taken as 1 MHz). Waveform generation and signal processing takes place in a PC running the Matlab environment with the Instrument Control toolbox.

The first step of our experimental procedure consisted in finding a system model for the complete transmission-reception process. For that purpose we excited the emitter with sequences of pseudo-random pulses designed so that their frequency content is in the band 0–100 kHz, and recorded the received signals. Next we applied the techniques of system identification [27] to the input-output sequences, and found an output-error (OE) model which was capable of reproducing the behavior of the system with high accuracy. The frequency response of the model is shown in figure 7, with a measured bandwidth of 16 kHz (-3 dB) centered at 40 kHz. Both amplitude and phase responses are quite nonlinear within the passing band. It seems likely that enhanced performance of the transducer system could be obtained by equalization of the ultrasonic channel [2]; however, we will not deal with this topic in this paper.

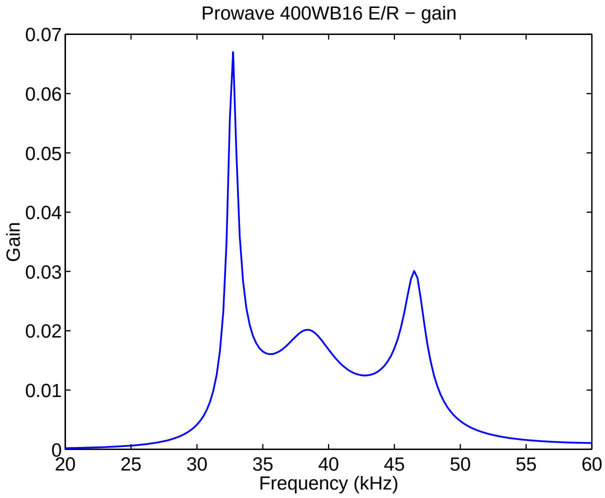


Figure 7: Frequency response gain of the transducers of figure 6.

The next logical step is designing a modulated waveform whose spectrum will fit into the bandwidth of the transducer system. As a standard waveform for the experiments, we settled for a 127 bits long Gold code, encoded with BPSK modulation and n_{cyc}=4 cycles/bit (total length of 12.7 ms). In figure 8 (a) we show the original spectral density of the signal, and in part (b), how it is changed by the processes of transmission and reception. Although they modify considerably the frequency content of the signals, the transducers chosen allow for a 15 kHz bandwidth, instead of merely 2 kHz as would be the case with resonant piezo-transducers.

In the following sections we will illustrate some of the characteristics of the modulation and codification of ultrasonic signals empirically.

6.1. Multi-user capacity

As was shown in section 2, the orthogonality of the digital codes permits simultaneous emission by several users. In this experiment, we have used two

[4] Circe is a research project funded by the European Union, whose goal is producing a functional replica of a bat's biosonar system. More information in the project webpage `http://www.circe-project.org`.

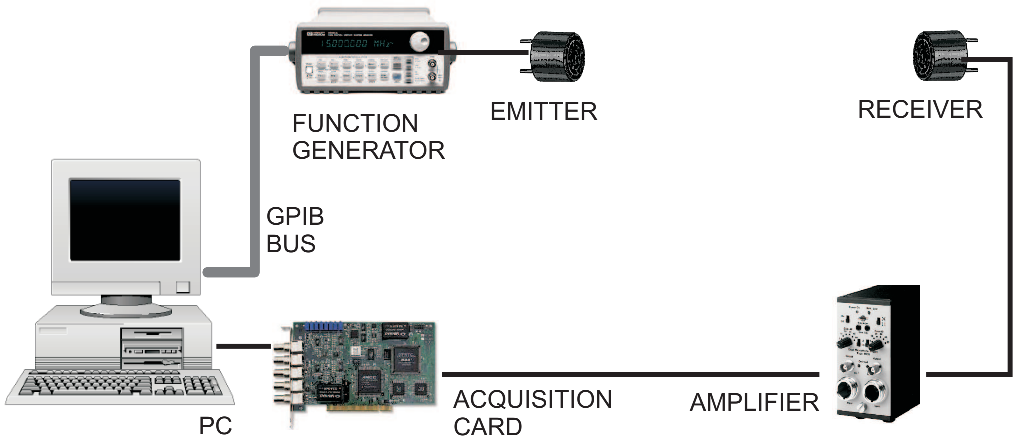


Figure 6: Experimental setup for the modulation and codification of ultrasonic signals.

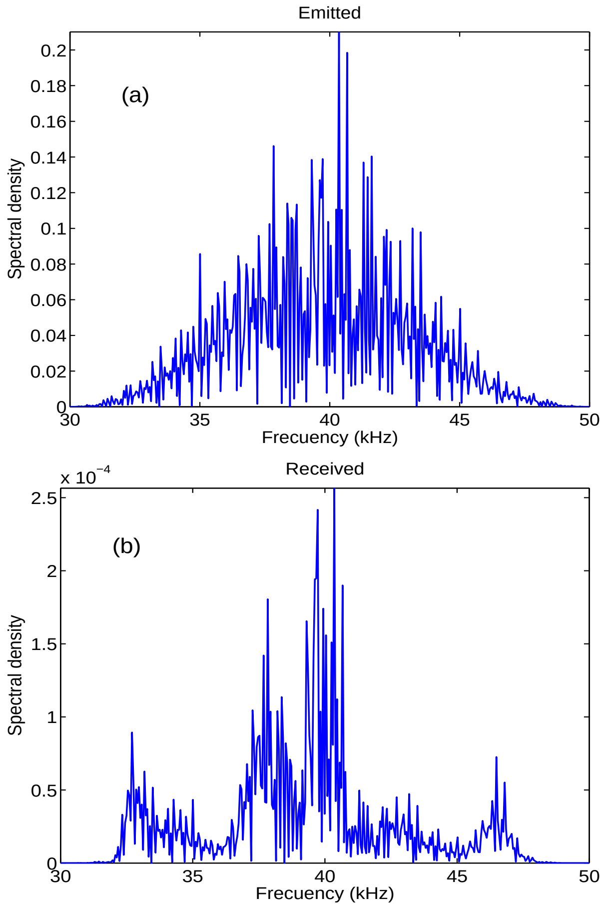


Figure 8: Spectral density of a modulated Gold code: (a) as emitted; (b) after reception.

closely placed ultrasonic transmitters, which emit synchronously two different Gold sequences. The received waveform is processed as indicated in section 2.3 and then correlated with each code to locate the individual echoes. The results are shown in figure 9 for two different separations of the emitters: (a) 53 mm, and (b) 3 mm (for comparison, the spatial length of the code is 4.3 m). Notice, in the second case, the considerable signal fading caused by the destructive interference between the two transducers. Even in these circumstances, the individual echoes are easily resolvable.

6.2. Processing gain and resistance to interference

We saw before that the processing gain provides a capability for working in low SNR environments or in the presence of interference from other sources; a feature which will be demonstrated now through a set of three different experiments.

In the first experiment the signal amplitude at the emitting transducer was lowered until a SNR of -6.4 dB is obtained. The signal, as shown in figure 10 (a), is hardly distinguishable from the noise. Actually, in part (c) of the same figure we can see that the spectral density is below the noise level for most frequencies. However, when the signal is correlated with the emitted code, a clear detection peak appears (figure 10 (b)).

In the second experiment the emitting transducer is transmitting the coded signal while another transducer placed very close emits a pure tone at 40 kHz with a relative amplitude 11.6 dB above the signal to be detected (see figure 11 (a)). This is a situation of narrowband noise interference right at the carrier frequency (see part (c) of the figure), in which most conventional detectors would be rendered useless. However, through processing gain we are able to detect the emitted signal, and obtain a clear correlation peak (figure 11 (b)).

Finally, the third experiment illustrates the resistance to wideband, impulsive noise. The acoustic energy produced by many mechanical phenomena contains both audible and ultrasonic noise which may cause malfunction of ultrasonic based systems. In this case we created wideband noise by shaking a set of metal keys right in front of the receiving transducer. The received waveform, shown in figure 12 (a), had an estimated SNR of about -15 dB,

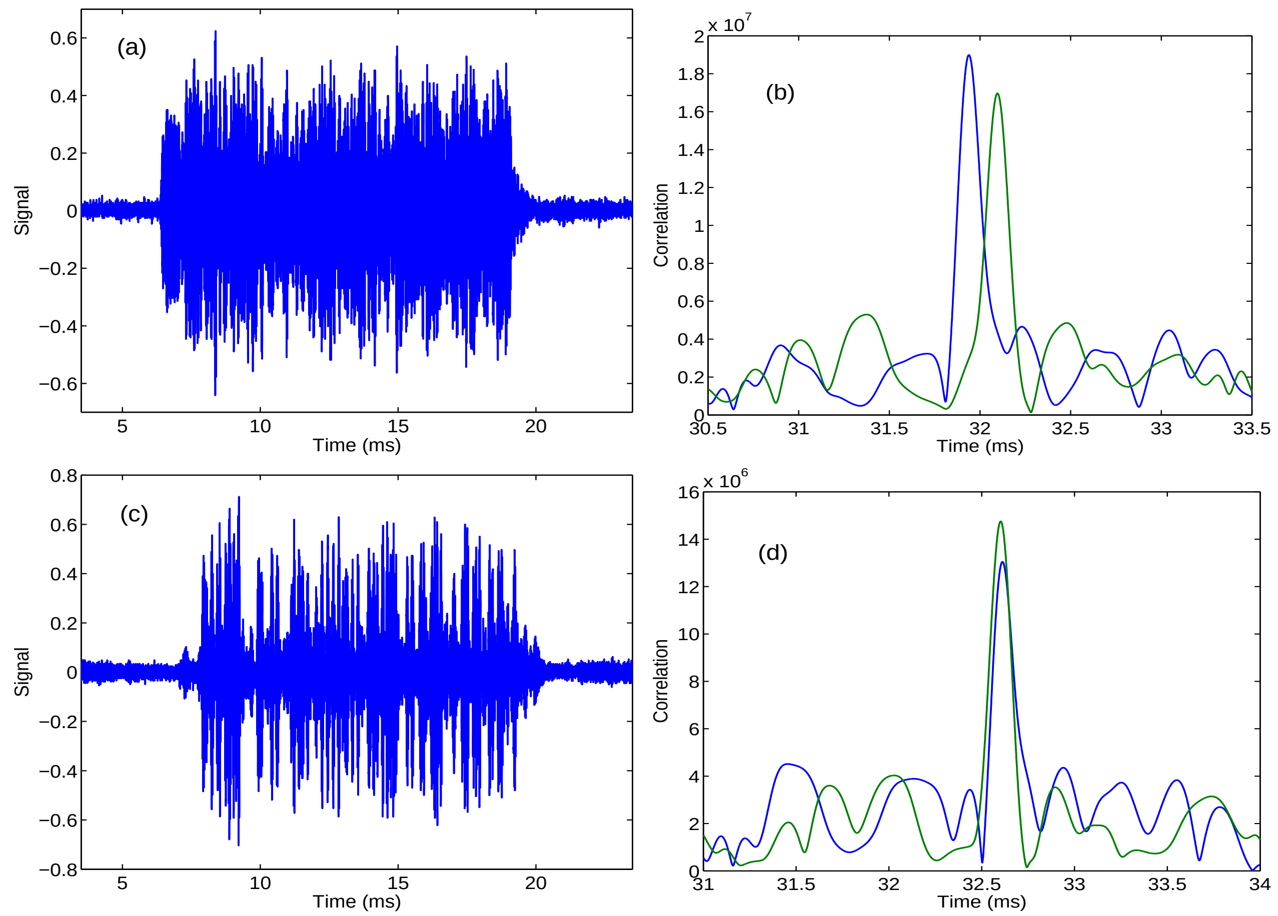
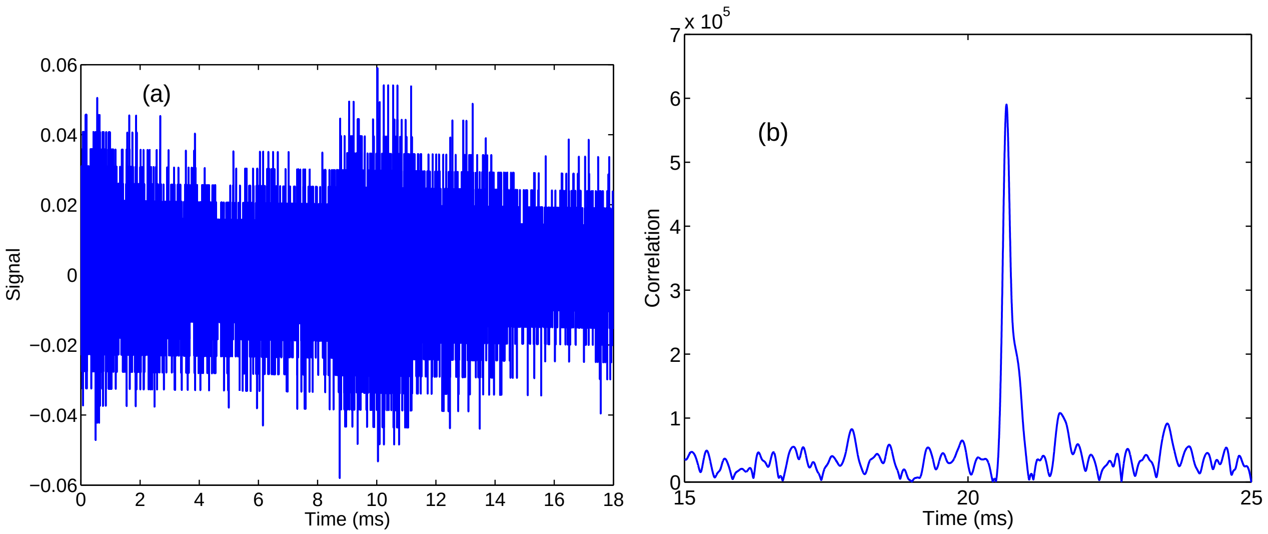


Figure 9: Echo separation capability of two orthogonal codes. In (a) the emitting transducers are separated 53 mm (156 μs); the correlations with each code are shown in (b). In (c) and (d) the transducer separation is 3 mm (8.7 μs).



and a noise spectra as shown in part (c). Again the correlation operator was able to produce a peak and detect the presence of the signal (figure 12 (b)).

As a conclusion, the processing gain takes advantage of the signal's structure and is able to detect the presence and time arrival of an ultrasonic echo in situations of low SNR or strong interference from other sources. The three cases shown cover many of the situations which degrade the performance of ultrasound based systems. Furthermore, the detection capability of processing gain is controllable by increasing the code's length.

6.3. Data transmission

Like any other communication channel, the ultrasonic transducers are able to transmit information

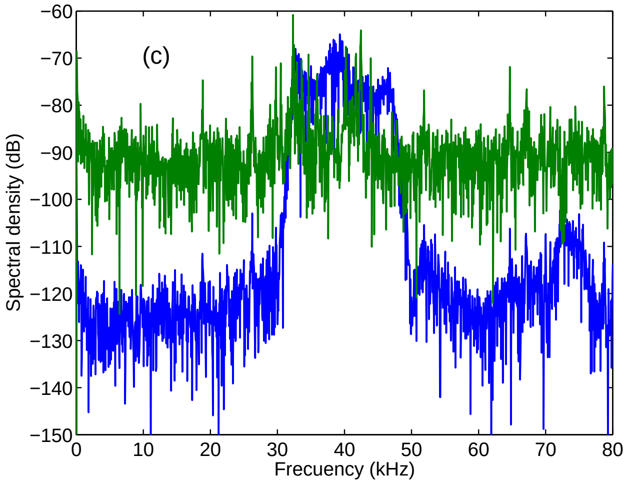
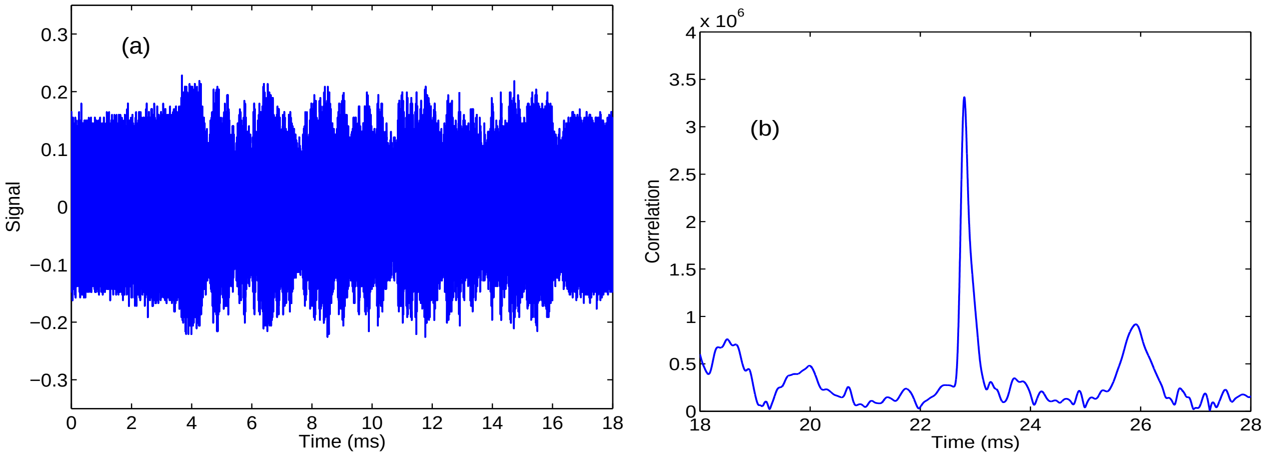


Figure 10: Signal detection for low SNR: (a) received signal, (b) correlation, and (c) spectrum of the signal (blue) and the noise (green).



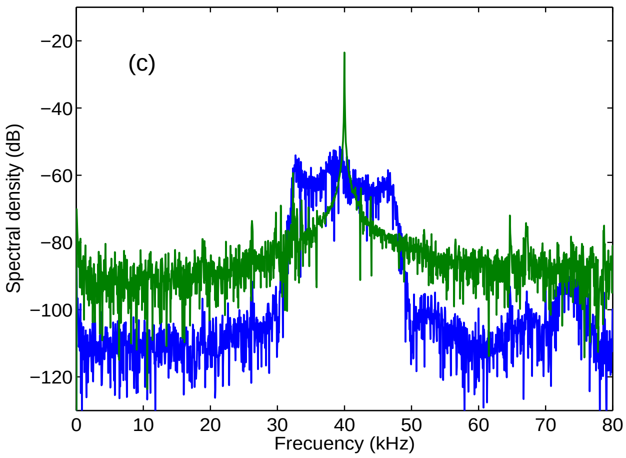


Figure 11: Signal detection with narrowband noise: (a) received signal, (b) correlation and (c) spectrum of the signal (blue) and the noise (green).

in the form of digital messages. To illustrate this point, we designed a signal waveform, which consists of a header, and a short digital message.

The header is needed because unless the position of the transducers is precisely determined (if, for example, they are mechanically fixed), the signal arrival time is unknown and the ultrasonic transmission is asynchronous. Then the header fulfills the purposes of detection and symbol synchronization.

The header is again a BPSK modulated Gold sequence of length 127, with 4 cycles per bit. The transmitted message is appended at the end of the header and it is a random 256 bits sequence modulated with QPSK, with 16 cycles per symbol (or 8 cycles per bit). A Gray code is applied to reduce bit errors. The length of a complete transmission signal is 64 ms; and excluding the header (which does not carry information), the transmission speed is about 4 kbits/s (about 1/15th of the speed of a 56k modem).

An experimental signal is shown in figure 13 (a), for a transducer separation of 1 m, and a resulting SNR of

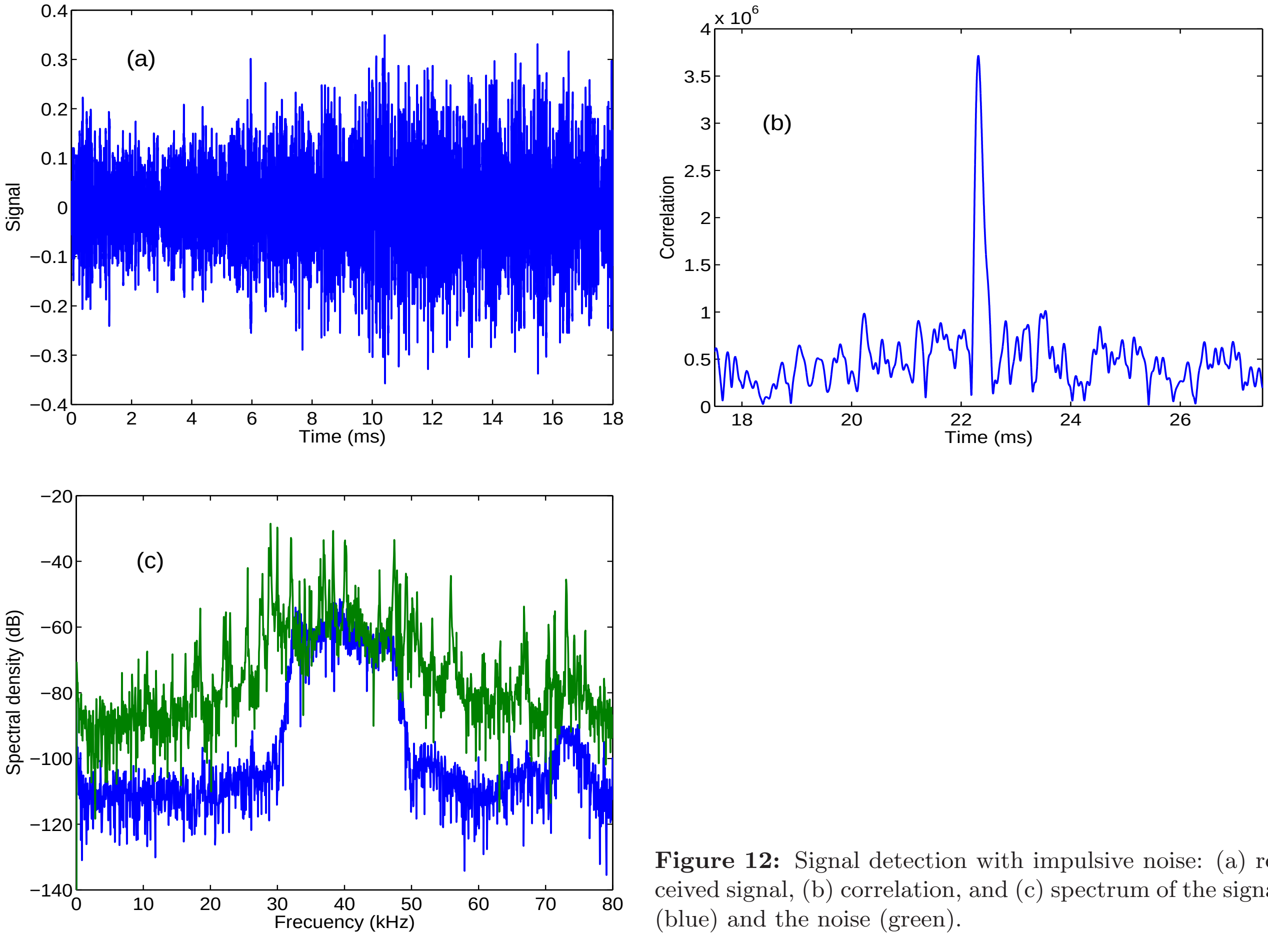


Figure 12: Signal detection with impulsive noise: (a) received signal, (b) correlation, and (c) spectrum of the signal (blue) and the noise (green).

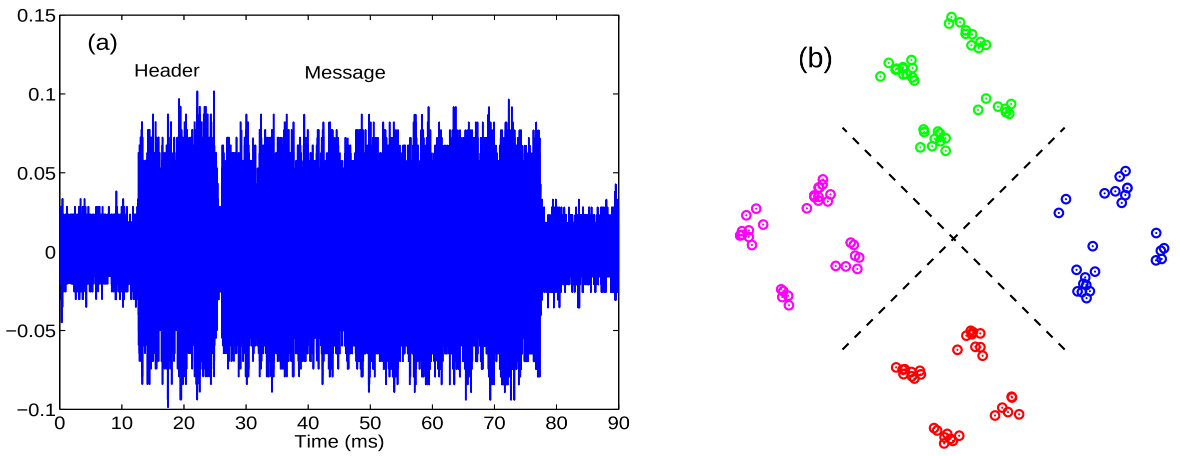


Figure 13: (a) Transmission signal, including the header and a 256 bits QPSK modulated message; (b) symbol constellation obtained after demodulation.

10 dB. As usual the signal is brought to the baseband and correlated with the header to obtain a 'delta'-like spike, providing synchronization for the position of the message symbols. A matched filter is applied to demodulate the symbols. The results are shown in part (b) of figure 13, which is the constellation of all possible phases (0, $\pi/2$, π and $3\pi/2$, corresponding respectively to the two-bit symbols 00, 10, 11 and 01), separated by the dashed lines.

For this relatively high signal amplitude (the SNR per bit was found to be 29 dB), the bit error rate is very low (in our case, the demodulator found all 256 bits correctly in several trials).

7. CONCLUSIONS

This paper has shown some of the advantages obtainable from the processing gain when signal codification and modulation are introduced in ultrasonic applications. Namely, they consist of: enhanced SNR and resistance to interference, higher precision in estimation processes, support for several users and possibility of data transmission through the ultrasonic channel. These features can be very useful for ultrasound-based positioning systems and the navigation of robots and autonomous vehicles.

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