# Modulation and Codification of Ultrasonic Signals with EMFi Transducers

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***Abstract*—The electromechanical film (EMFi) is a thin polypropylene film with electret properties, high flexibility and large bandwidth. Ultrasonic transducers built with EMFi film can overcome the limited bandwidth of currently available transducers for air applications, and permit the use of spread spectrum CDMA (Code Division Multiple Access) signal processing techniques, with potential benefits in many ultrasonic applications. In this communication we report the use of CDMA techniques with custom built EMFi transducers, applying signal modulation and codification and processing gain for enhanced signal detection and ranging.**

## I. Introduction and Objectives

The electromechanical film (EMFi) is a thin polypropylene film with electret properties that has been introduced in the last years as a new material for sensors and actuators [1]. Its potential for ultrasonic applications in air, due to its high flexibility and large bandwidth, has also been recognized [2]. This material opens the possibility to overcome some of the limitations of currently available transducer technology, permitting conformation of the ultrasonic field and broadband frequency response.

In particular, EMFi-based ultrasonic transducers permit the use of spread spectrum CDMA (Code Division Multiple Access) signal processing techniques with potential benefits to many ultrasonic applications: simultaneous operation of many transducers, increased resistance to noise obtained through processing gain, and higher measurement accuracy. In this research we explore experimentally the benefits of CDMA modulation and codification of ultrasonic signals with custom-built EMFi transducers.

### *A. CDMA modulation and codification of ultrasonic signals*

Code division multiple access (CDMA) is a standard communications technique that permits that many users (or transmitters) utilize simultaneously the same frequency band of a communication channel. CDMA is an alternative to multiplexing in time (TDMA) or in frequency (FDMA) and it's widely used in today's telecommunication systems, like, for example, mobile telephony. CDMA works by digitally modulating each transmitted signal with an identification code proper of each transducer, which can be decoded upon reception of the signal [3].

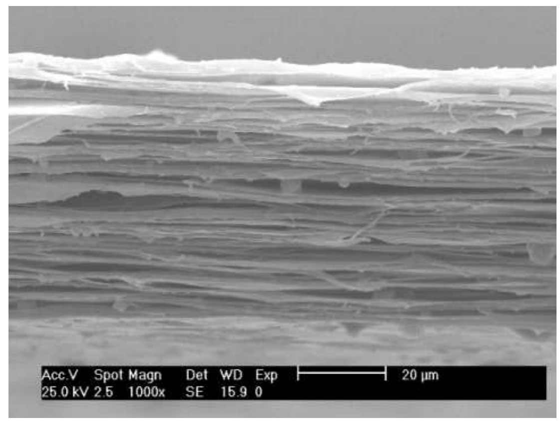


Fig. 1. Microphotography of the electromechanical film used in this paper, showing its internal, bubble-like structure.

### *B. Advantages and applications of ultrasonic CDMA processing*

We will mention briefly the advantages obtained by CDMA modulation and codification of ultrasonic signals. First, simultaneous operation of several transducers is available with reduced crosstalk between them. Second, enhanced precision in estimation processes can be achieved (for example, accurate ranging in a positioning system). This property stems from the large signal's bandwidth and duration product ($BT$) available with coded waveforms, which decreases the Crámer-Rao lower bound [4]. Finally, processing gain, obtainable by taking advantage of the signal's structure, is directly proportional to the number of bits $N_b$ of the encoded signal. Processing gain permits to detect low amplitude signals (even below noise level) and provides resistance to interference from noise sources and other users.

CDMA modulation and codification of signals has found applications within the ultrasonics field, mainly in medical ultrasound [5], and non-destructive testing and non-contact ultrasonic imaging [6].

Likewise, recently developed ultrasound-based local positioning systems [7] [8] employ CDMA techniques for simultaneous operation of several transmitters, faster performance,

Fig. 2. Emitting (flat) and receiving (cylindrical) transducers fabricated with EMFi film.

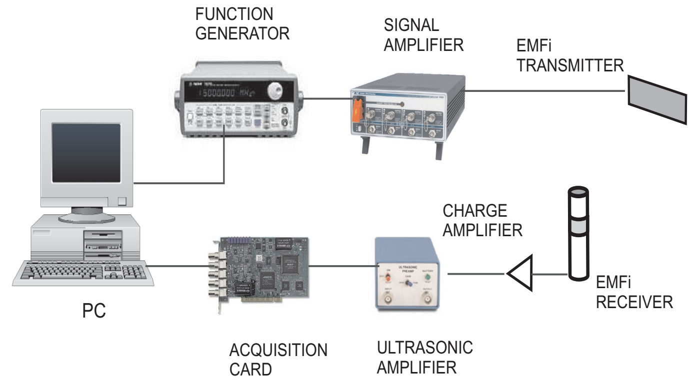


Fig. 3. Experimental setup for transmission and reception of CDMA ultrasonic signals with EMFi transducers.

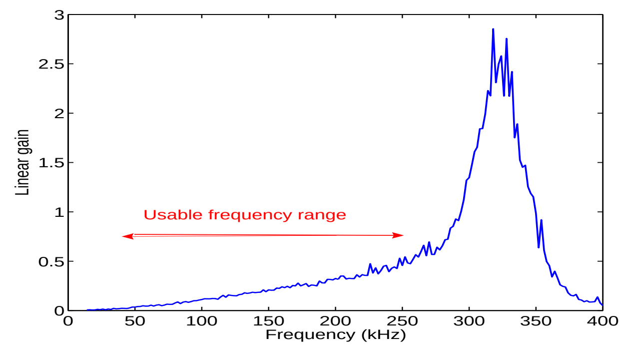


Fig. 4. Frequency response gain (linear plot) of the transducer system, and usable frequency range considered in this work.

and increased positioning accuracy, much like the GPS system.

Ultrasonic sonar use CDMA processing to extract more information from the environment than merely the range and bearing to the nearest obstacle provided by conventional sonar systems. For example, obstacle classification capability is obtained with a sensor system formed by two emitters and four receivers operating simultaneously, described in [9], where Golay complementary pair sequences modulated with QPSK are used for each transmitter. A related trend of ultrasonic sonar research aims at replicating the sonar systems of living creatures, particularly those used by bats in navigation and hunting [10].

A recent investigation much along the lines of the present work is described in [11], where a transducer setup for transmission of broadband signals with EMFi transducers is investigated, with encouraging results found.

In this paper we describe a preliminary experimental research of the use of EMFi transducers for CDMA codification and modulation of ultrasonic signals for air applications. The next section describes our experimental apparatus, while section III shows empirical results. Discussion of these and conclusions are offered in section IV at the end of the paper.

## II. Experimental Setup

The EMFi transducers fabricated for this research are shown in Fig.2. The transmitter is flat, with a width of 120 mm and a height of 40 mm, while the receiver is cylindrical, with a diameter of 24 mm and a height of 20 mm. Both are built with a single layer of film provided by Emfit Ltd. (Vaajakoski, Finland), product number HS-03-20BR AL1 (further description of the film is given in reference [2]).

The general setup is shown in Fig. 3. The transmitted signal is created in a PC and transmitted to an Agilent Technologies 33120A arbitrary function generator (15 MHz bandwidth, 12-bit resolution) through the GPIB bus. The excitation signal is amplified by 40 dB by Tabor Electronics 9400 wideband amplifier (DC to 500 kHz, 4 channels), with a resulting amplitude of 200 Vpp. The received ultrasonic signals are processed with a charge amplifier, followed by a Panametrics model 5660C wideband amplifier (DC to 2 MHz, 40/60 dB), and finally acquired into the PC with an Adlink PCI-9812 acquisition card (sampling frequency 5 MHz). Waveform generation and signal processing take place in the Matlab environment in a PC.

## III. Experimental Results

### A. Frequency response

The usable frequency range of a single layer EMFi transducer in air is DC to 350 kHz, with transmitting SPL of up to 95 dB at 30 cm; these characteristics can be changed by stacking several layers of the film. The experimental frequency response is shown in Fig. 4.

Analytical results for the far-field radiation of the emitter transducer were computed with the stationary phase method [12]. The acoustic field at 150 kHz is quite narrow, producing a lobe of width 0.01 rad in the horizontal direction, and 0.026 rad in the vertical direction (amplitude drop of -3 dB). Although this implies a relatively careful positioning of the transducers, it permits successful signal transmission at a distance of 0.5 m in spite of the high attenuation caused by air at this frequency of operation.

### B. Emission and reception of a single code

In this paper we will use binary phase modulation (BPSK), which consists in encoding the transmitted message (a sequence of bits $g[n]$) into the phase $\phi(t)$ of the carrier signal:

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

where $n_{\text{cyc}}$ cycles of the carrier are used for every bit of the message, and $\phi(t)$ shifts by $\pi$ radians as the bits change.

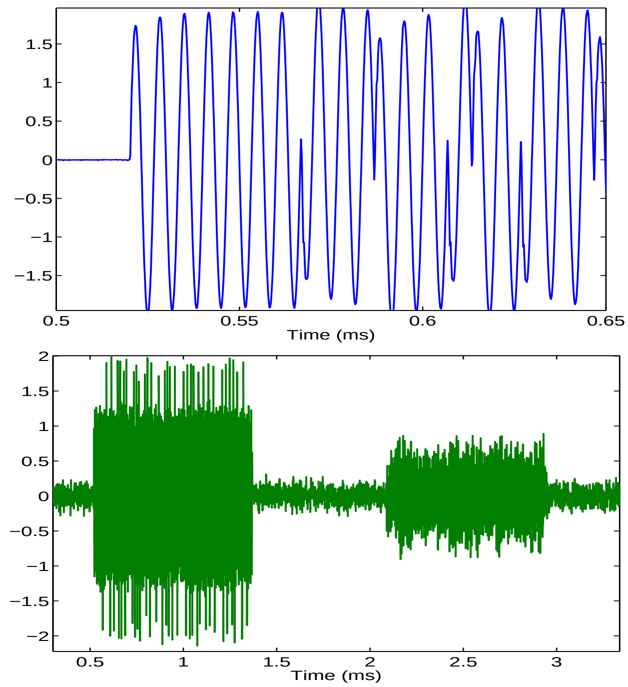


Fig. 5. (Top) Initial part of the excitation signal of the emitting transducer, showing phase changes of BPSK modulation (carrier frequency $f_0 = 150$ kHz). (Bottom) received signal. The first part corresponds to electromagnetic coupling between emitter and receiver, the second part to the acoustic signal.

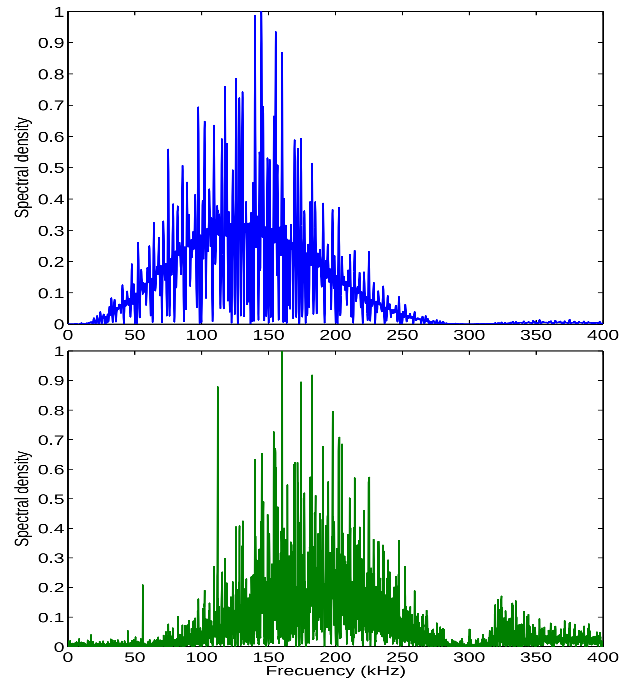


Fig. 6. Spectral densities of the emitted (top) and received (bottom) ultrasonic signals. The excitation signal is broadband, occupying a wide frequency range between 50 and 250 kHz The spectral density is not seriously modified by transmission, although some higher gain at high frequencies can be appreciated, as well as the effect of the resonance at 325 kHz.

This method of signal modulation performs well in our case; indeed, other researchers [13] have found it superior over alternative modulation techniques.

The carrier frequency $f_0$ must fall in the usable frequency range of the EMFi transducers shown in Fig. 4. Not surprisingly, the best results are obtained at central frequencies near the middle point of that region.

In consequence, we transmitted a BPSK-modulated Gold code signal, with $N_b = 127$ bits, carrier frequency equal to 150 kHz and 1 cycle/bit. The duration of the signal is 847 $\mu$s, corresponding to 290 mm in air; its initial portion is shown in the top part of Fig. III-B. The received signal is shown below it (the separation between the transducers is 0.5 m). After the electromagnetically coupled signal, we can see the transmitted signal through air.

The spectral density of the emitted and received signals are shown in Fig. 6. As it can be seen, it occupies a large part of the available frequency range, but the received signal is not significantly filtered out.

Detection of the signal emitted is achieved by correlation with the transmitted digital code $g_i[n]$:

$$R_{ri}[m] = \sum_n r[n] g_i[n+m]. \quad (2)$$

Ideally, for a set of nearly orthogonal codes, $R_{ii}[m] =\simeq \delta[m]$ and $R_{ij}[m] =\simeq 0$, where $\delta[m]$ is Kronecker's delta. Pseudo-random codes $g_i[n]$ like Gold sequences resemble approach these conditions, and permit to identify several users operating at the same time.

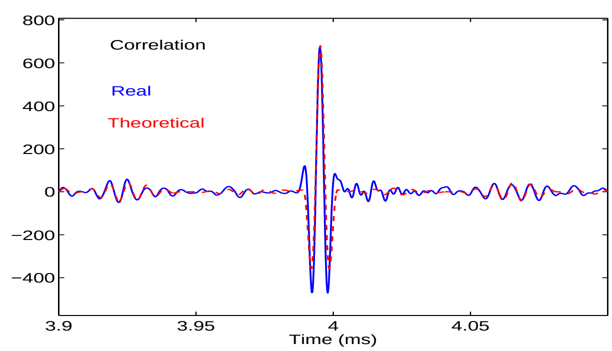


Fig. 7. Correlation of the received signal (blue) and comparison with theoretical correlation (red).

It can be seen in Fig. 7 that the obtained correlation is spike-like and coincides almost perfectly with the ideal correlation, indicating that little distortion has been introduced by the ultrasonic channel. This is useful since it permits easier signal detection in noisy conditions (low SNR) and accurate temporal measurements (higher ranging resolution).

### C. *Correlation of code with frequency sweep*

As shown in Fig. 8, the peak correlation deteriorates when the central frequency $f_0$ of the excitation signal moves away from 150 kHz. At low frequencies the response of the EMFi film decreases, while at high frequencies the resonance peak of the film at 325 kHz begins to dominate the response and

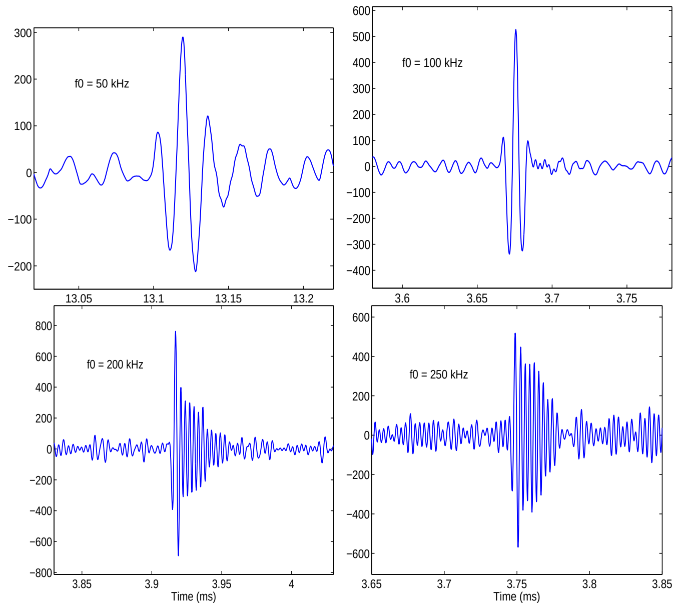


Fig. 8. Correlation of emitted codes at different central frequencies $f_0$ (50, 100, 200 and 250 kHz). The amplitude of the correlation peak decreases at low frequencies and it starts to ring as we approach the resonance frequency of the film (325 kHz).

distorts the received waveforms.

## IV. Discussion and Conclusions

This paper has explored the capabilities of EMFi-based transducers in a direct transmission setup in air. Phase-modulated signals carrying a binary code can be used for air transmission by taking advantage of the large usable bandwidth of the EMFi film (in our sample, from audible frequencies up to the resonance frequency at 325 kHz).

We have found that this setup outperforms other wideband ultrasonic systems like, for example, Prowave piezoelectric 400WB16 'wideband' transducers operating at 40 kHz [3]; however, a rigorous comparison with the capacitive and PVDF technologies is needed.

An equalization of the ultrasonic channel to compensate the varying frequency gain at different frequencies within the signal's bandwidth could be done for enhanced performance of the system [14].

Due to its flexibility, the EMFi film also permits a degree of control over the acoustic emitted field. So far several practical setups have been described by our group [2], with interesting properties for manipulation of the acoustic field. The main drawback of EMFi-based transducers in the setup discussed in this communication is its relatively low transmissivity and receiving sensitivity, when compared with other currently used transducers (piezoelectric, capacitive and PVDF). This factor is aggravated if higher frequencies are used, due to the increasing ultrasonic absorption in air. In spite of this, we have obtained usable signals over distances of 1 m and higher with EMFi transducers.

We are also experimenting with stacks of several layers of the EMFi material. This permits a modification of the natural frequency response of the material, as shown in a companion paper to this communication [15], and possibly enhanced signal gain below resonance.

In conclusion, this paper has shown the advantages of using CDMA modulation and codification of ultrasonic signals with EMFi transducers: processing gain, higher estimation accuracy and support for several users simultaneously. Potential applications of these features include the fields of local positioning systems, navigation of robots and autonomous vehicles, nondestructive testing, and biomimetic systems.

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