Neither PAS nor CAS: MIMO

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***Abstract*—In this paper, we discuss the PAS (Pulse Active Sonar) and CAS (Continuous Active Sonar) strategies for target detection and tracking. CAS system potentially offer several advantages over traditional PAS systems, mainly in term of probability of detection and/or tracking. With a continuous insonification of the target, CAS can track continuously limiting the data association error inherent to PAS system. Recent works in MIMO (Multiple Input Multiple Output) radar and sonar have bring new solutions for the orthogonal waveform design problem. We present here a modified CDMA (Code Division Multiple Access) waveform adapted to sonar constraints. Using such waveforms offers a mid-way solution between PAS and CAS allowing the user to decrease the PRI (Pulse Repetition Interval) and then increasing the hits on target but not at the cost of sacrificing the full bandwidth.**

I. Introduction

Traditional active sonar systems are PAS (Pulsed Active Sonar). With low duty cycles (typically 1% or lower), the receivers are usually switched off during the transmission to avoid the direct blast which can saturate the system. Recently CAS (Continuous Active Sonar) systems have gained a lot of interest, especially in the ASW (Anti-Submarine Warfare) community [1]–[5]. Although the ideas behind CAS are not new, only recent technological improvements have made CAS feasible. With close to 100% duty cycles, CAS systems have several advantages compared to PAS systems. First, the time-bandwidth product is massively increased, which results in an important gain toward incoherent noise. It is important to note that this capability will increase detection in a deep water scenario but not necessarily in shallow water where the limiting factor is linked to coherent clutter. The second important factor came from the fact that with CAS systems the target is constantly insonified. The tracking performances are then improved thanks to a constant tracking of the target and not a discreet one. The continuous tracking decreases drastically the complexity of the data association step. CAS waveforms are usually continuous transmission FM across the bandwidth available from the system. CAS are then traditionally limited to one single transmitter. This paper aims to tackle this specific issue: we propose a solution which allows multiple transmitters to be operational at the same time while keeping the full bandwidth available for each transmitters and with increased PRI (Pulse Repetition Interval).

Recent research in MIMO (Multiple Inputs Multiple Outputs) sonar systems have investigated the orthogonal waveforms problem. In this paper we investigate a mid-way solution in-between PAS and CAS for waveform design allowing the use of several transmitters and with increased PRI.

Orthogonal waveforms are a subject of interest of the MIMO community and can be divided into three categories: TDMA (Time Division Multiple Access), FDMA (Frequency Division Multiple Access) and CDMA (Code Division Multiple Access). TDMA refers to waveform sets which share the same frequency band but not at the same time. FDMA refers to waveform sets which occupy different frequency band at the same time. Finally CDMA refers to waveform sets which share the same frequency band at the same time. The intrinsic problem related to TDMA is the PRI. The PRI increased linearly with the number of transmitters. Bandwidth is a rare resource and FDMA design divides the full bandwidth by the number of transmitters. CDMA have been investigated intensely in a radar context. However the radar constraints are very different from the sonar transducer constraints. Radars, in particular, use traditionally non-linear power amplifier to maximise the output power. As a consequence, the radar waveform has to have constant amplitude. On the another hand, the phase of the pulse can change very rapidly. All the CDMA have been designed around these requirements. Sonars systems are not constraint to constant amplitude pulses, however the piezo-electric material which forms does not allow rapid phase transition.

We developed modified CDMA waveforms to be compliant to the transducers constraints in particular in term of phase continuity. The waveforms are the result of the concatenation of two micro-chirp series and respond to the following requirements: the full bandwidth is covered for each pulse, the waveforms show *"good"* auto- and cross-correlation, the waveforms have smooth phase transition, a large number of orthogonal waveform can be generated. We will also propose optimisation algorithms to take into account the number of transmitters, available bandwidth and desired duty cycles. Numerical simulations will show the benefits of such waveforms.

The paper is organised as follows: in section II, we described the PAS and CAS strategies, highlighting the advantages and disadvantages of the two techniques. In section III, we first described the three traditional waveform designs used by the radar community and put them in perspective regarding sonar implementation. Finally in section IV, we proposed a modified CDMA waveform family which match the sonars' transducer constraints.

II. PAS and CAS systems

In the following section, we note T the pulse duration and B its effective bandwidth.

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A. Pulsed Active Sonar

With a PAS system, a short pulse (typically 1% duty cycle) is first transmitted, the echo is then recorded. Figure 1(a) pictures a time-frequency representation of a PAS system insonifying a target. Measuring the time between the pulse and the target echo gives an estimate of the target range. Note that the target is seen one time per PRI (Pulse Repetition Rate).

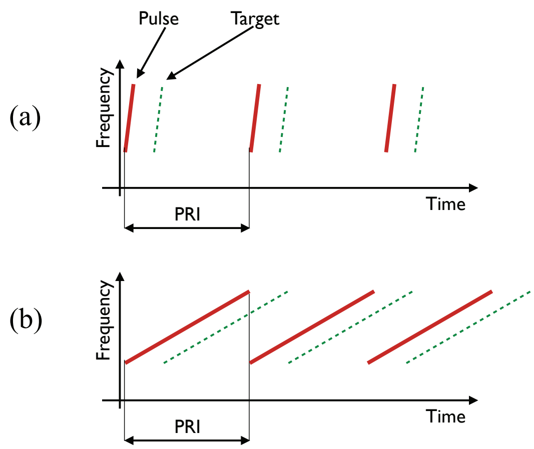


Fig. 1. Time-frequency representation of (a) PAS and (b) CAS system insonifying a target. Pulses are represented by a red line, the target response by a green line.

B. Continuous Active Sonar

Although the concept behind CAS is not new, only recent technological developments have allowed its exploitation [1]–[4]. Figure 1(b) pictures a time-frequency representation of a CAS system insonifying a target. CAS systems often use CTLFM (Continuous Time Linear Frequency Modulation) pulses whose swept time equals the PRI (for a 100% duty cycle pulse).

There are two main advantages that CAS systems can procure. First, as we can see in Figure 1(b), the target is *"seen"* continuously, and proper CAS processing should allow a continuous tracking of the object of interest. The second advantage is derived by the following gain processing results:

In a noise limited environment such as a deep water environment and after pulse compression, the signal-to-noise ratio (SNR) is given by:

$$\mathrm{SNR} \propto 10 \log_{10} T \tag{1}$$

While in a clutter limited environment (coastal environment), the signal-to-reverberation ratio (SRR) after pulse compression is given by:

$$\mathrm{SRR} \propto 10 \log_{10} B \tag{2}$$

From Eq. (1), it appears that in a deep water environment the longer the pulse, the higher the probability of detection. CAS could potentially gain drastically in term of SNR. Because the target is potentially moving, it may be difficult to integrate the signal for the full PRI. One of the challenge of CAS is then to chose appropriately the window of integration [3]–[5]. Abraham in [5] for example was able to link the target PDF and the bandwidth via a gamma- fluctuating-intensity signal model.

However, by processing the signal in sub-band, one losses the processing gain given by the full bandwidth (cf. Eq. (2)). In the next sections, we discuss how the CDMA pulses developed for MIMO purposes can bring a solution to this specific problem of pulse design.

III. Waveform design for MIMO radar

A. TDMA: Time Division Multiple Access

TDMA refers to Time Division Multiple Access. It refers to waveform sets sharing the same frequency band but not at the same time. Pulses are transmitted successively at regular interval Δ_τ called the pulse repetition interval (PRI). This strategy is by far the most commonly used for multi-static sonar systems. And as long as Δ_τ is large enough for the echo response to drop below the detection threshold, the TDMA waveforms are quasi-orthogonal. The intrinsic problem with TDMA is related to the dynamic of the scene. In an ASW context for example, one may require to survey a large area. If the maximum distance is 40km, taking into account the relatively slow sound speed in water, the PRI can be as high as 1 minute. A 15 knots target then could potentially move $\frac{1}{2}$km between pings. The tracking performance related to such system would then be diminished by the rapidly growing position uncertainty and the data association complexity.

B. FDMA: Frequency Division Multiple Access

FDMA refers to Frequency Division Multiple Access. In this case, the waveform set occupies different frequency bands at the same time. As long as the frequency bands of each waveform are well separated, the waveforms are almost orthogonal. Different strategies have been explored to implement FDMA depending on the slicing of the available frequency band. Each pulse can occupy for example a different continuous frequency band or having finely interleaved frequency supports. For active sonar however, the bandwidth is a rare resource. Assuming identical transmitters, a FDMA approach results in dividing the full bandwidth by the number of transmitters and then potentially losing all benefit of wideband systems including SNR and resolution gain.

C. CDMA: Code Division Multiple Access

Due to the restrictions of the two previous approaches, a lot of effort has been put in CDMA (code division multiple access) approaches. CDMA waveforms include polyphase code, pseudorandom phase codes, up and down chirps or codes such as Baker or Gold codes. The main criteria for MIMO waveform optimisation are the sidelobe level and cross correlation. Several optimisation solutions were proposed using SA (Simulated Annealing) algorithms [6], [7], Bee algorithms [8] or maximal length sequences [9]. In [10], Rabideau introduces another metric to measure the fitness of MIMO waveforms by considering the maximum amount of interference that can be cancelled. He then applied his metric for clutter reduction adaptive MIMO system. Another approach to CDMA waveform design is to relax the orthogonality hypothesis and optimising the waveform covariance matrix according to a given criterion. Forsythe in [11] for example computed the covariance matrix which maximises the image intensity. Li then proposed in [12] a cyclic algorithm to compute the covariance matrix under the constant amplitude constraint. In [13], Yang derives optimum waveform design to maximise MI (Mutual Information) and minimise mean-square error (MMSE) for the target response estimation.

IV. Orthogonal waveforms for MIMO sonar

Radar designs and electronics impose a certain number of constraints on the waveform design. One of the most restrictive constraint is due to the non-linear amplifiers used for such systems and it imposes to the radar waveform a constant amplitude. Although the constant amplitude requirement maximises the pulse energy, it drastically reduces the degrees of freedom. The radar community then find efficient solutions to manipulate the signal phase including phase shift. Figure 2 provides an example of phased coded radar used in [9]. For active sonar system, pulse emission is the result of piezo-electric material excitation via linear amplifiers. Sonar systems are then not constraint to pulses with constant amplitude. The transducers however cannot handle drastic phase shifts and phased coded waveforms may be extremely distorted through piezo ceramic PZT (Lead Zirconate Titantate) transducers.

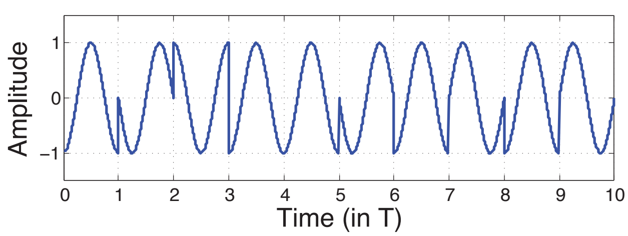
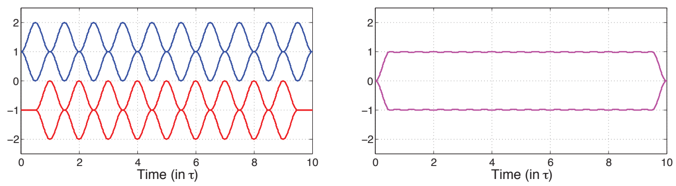


Fig. 2. Example of phased coded radar waveform.

So far only TDMA or FDMA waveforms have been tested for orthogonal waveform design. The only exception is the CDMA waveforms known as up and down chirps. The up and down chirp strategy however only provides two pseudo-orthogonal pulses and it is then inadequate for large MIMO systems. In this section we propose a CDMA strategy which fits the requirements of wideband large MIMO sonar systems:

1) wideband width covered by every pulses
2) *'good'* auto- and cross-correlation functions
3) possibility to generate a large number of orthogonal waveforms
4) waveforms with smooth phase transition
5) waveforms with relative constant amplitude

Note that if sonar amplifier electronics relax the strict constant amplitude constraint, a relative constant amplitude helps to maintain a high energy pulse and then maximise the signal to noise ratio. To fulfil the requirements previously stated, we propose to build the MIMO sonar waveforms using interlaced micro-chirp series (IMCS) with constant bandwidth. The waveform is the summation of two concatenations of micro-chirps series. Each micro-chirp has the same duration τ. The second micro-chirps series is time shifted relative to the first one by a factor of $\frac{\tau}{2}$. Figure 3(a) draws the envelops of interlaced two micro-chirp series.



(a) (b)

Fig. 3. *(a)* envelops of the first and second concatenated micro-chirps series (respectively blue and red curves). *(b)* full IMCS waveform envelop.

Each micro-chirp has the same duration τ and the same windowing. In this paper we chose the Hann tapering window. The windowing function has a threefold purpose:

- it smoothes the phase transition between each consecutive micro-chirp
- it ensures a relatively constant amplitude for the overall waveform (as shown in Fig. 3(b))
- it constrains the micro-chirp to a constant bandwidth

The full available bandwidth B is divided into N_B equal sub-bandwidth. The size of the minimal sub-bandwidth is given by the micro-pulse duration τ and the windowing function and can be approximated in our case by $1/\tau$. N_B can then approximated by $B.\tau$.

The duration of the full waveform is $\tau.N_\tau$ where N_τ is the number of micro-chirps of the first μ-chirp series. Each μ-chirp is chosen randomly between the N_B sub-bands with a random up or down chirp structure. The randomised up or down structure minimised the cross-correlation as well as the sidelobes in the auto-correlation function. Figure 4 draws an example of IMCS waveform structure in the time-frequency plane. Blue and red segments represent respectively the μ-chirp structure of the first and second μ-chirp series in the time-frequency plane.

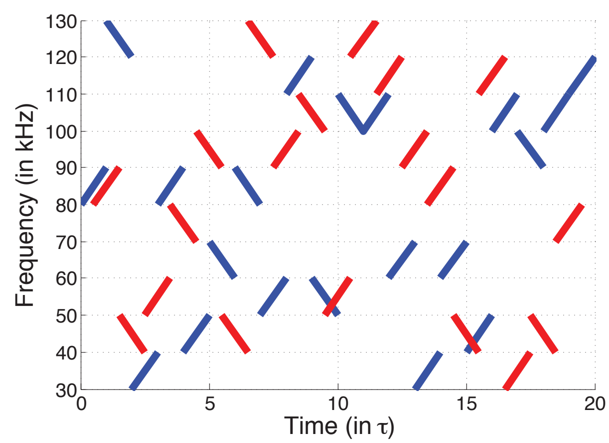
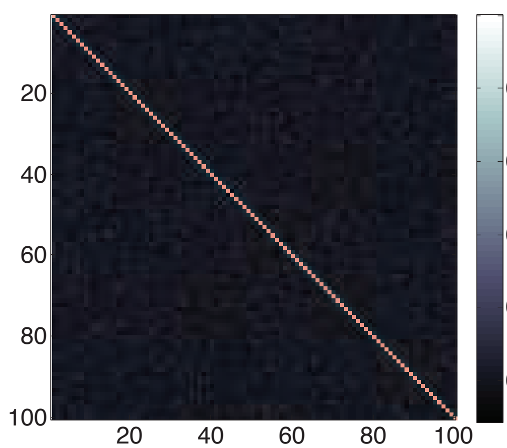
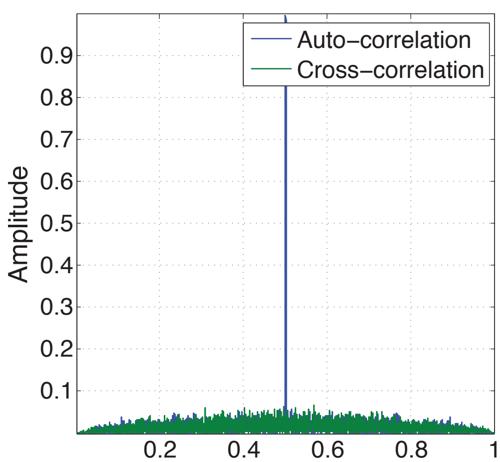


Fig. 4. Example of an IMCS waveform structure in the time-frequency domain. The blue segments represent the micro-chirps of the first series, the red ones represent the second series.

Theoretically there are $(2N_B)^{2N_\tau - 1}$ different waveforms. We computed 100 different waveforms for B = [30 kHz - 130 kHz], $\tau = 10^{-4}$s, $N_B = 10$ and $N_\tau = 90$. Figure 5(a)



(a)



(b)

Fig. 5. (a) Waveform covariance matrix. (b) Example of auto-correlation (blue curve) and cross-correlation (green curve) functions of the proposed waveforms.

displays the waveform covariance matrix. For perfectly orthogonal waveforms, we expect the covariance matrix being the identity matrix I_N. Figure 5(b) shows the auto-correlation function and very low cross-correlation function of one particular waveform.

Using the IMCS pulses in an ASW scenario offers two main advantages over CTLFM pulses:

1) Decreased PRI: several orthogonal pulses can be transmitted during one PAS PRI. If the tracking is not continuous as in CAS, the potential hit on target is multiply of the number of pulses sent during one PAS PRI period.
2) Multiple transmitters: several transmitters sending orthogonal pulses can be used in such scenario, increasing the view diversity and the overall coverage.

V. Conclusion

In this paper, we discussed the PAS and CAS strategies for midwater target detection and tracking. CAS potentially bring a lot of benefits in term of probability of detection or continuous tracking. But by processing the CAS signals in sub-bands, ones losses the full bandwidth gain. We proposed a mid-way solution in term of pulse design based on MIMO waveform design. The proposed IMCS combines the coverage of the full frequency band for each waveform, very low cross-correlation functions and minimal sidelobes for the auto-correlation functions.

Acknowledgment

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) Grant number EP/J015180/1 and the MOD University Defence Research Collaboration in Signal Processing EP/K014277/1.

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