Signal Processing 106 (2015) 88–105

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Review

Spreading sequences in active sensing: A review

Enrique García [a],*, José A. Paredes [b],**, Fernando J. Álvarez [b], M. Carmen Pérez [a], Juan Jesús García [a]

[a] *Department of Electronics, University of Alcalá, E-28871, Spain*
[b] *Department of Electrical Engineering, Electronics and Automation, University of Extremadura, Spain*

ARTICLE INFO

Article history:
Received 14 December 2013
Received in revised form
11 May 2014
Accepted 2 July 2014
Available online 15 July 2014

Keywords:
Spreading sequences
Active sensing
Matched filter
Ambiguity function

ABSTRACT

Active sensing is a growing research field with long-standing open problems, whose applications range from CDMA communication systems, ultrasonic imaging or ranging systems to name a few. In those applications, spreading sequences are usually transmitted in a bursting manner, making their aperiodic correlation the most important feature to be considered, since it determines how easily the transmission can be detected by the receiver. Hence, the selection of the spreading sequence with good aperiodic correlation properties has a large impact on the final system performance. This paper presents a revision of the aperiodic spreading sequences used for active sensing systems available in the literature so it aims to serve as a reference for researchers in the field.

Contents

1. Introduction and preliminaries

Active sensing for ranging measurements dates from the beginning of the twentieth century, with the patent on “Telemobiloscope” by Christian Hülsmeyer, for ships detection in 1904, being a precursor of what is currently known as RADAR. The first ranging systems, limited by the

---

* Corresponding author. Tel.: +34 918856592.
** Corresponding author.

E-mail addresses: enrique.garcia@depeca.uah.es (E. García), japaredesm@unex.es (J.A. Paredes).

http://dx.doi.org/10.1016/j.sigpro.2014.07.002
0165-1684/

state of the art of electronic devices, used envelope detection, obtained by rectifying the received signal and integrating it over time. These systems have several drawbacks that can be summarized as:

- Low immunity to noise, so if there are interferences in the working frequency band it would be possible to exceed the threshold regardless of not receiving the signal of interest.
- Low ranging accuracy, due to the unfeasibility of determining the exact time instant in which the signal of interest is received.
- Difficulty to work properly in multiuser environments.
- Low update rate.

During the last decades, spreading sequences have been extensively used to deal with the limitations of traditional ranging systems. Nonetheless, spreading sequences are not only used for carrying out ranging measurements like in GPS systems, RADAR or SONAR, but also for many other applications such as 3G synchronization preamble [1], CDMA mobile communications [2], phase-array systems [3] channel estimation [4], increase Signal-to-Interference-plus-Noise Ratio (SINR) in communications systems [5] or to contribute to the minimization of the Crámer–Rao Lower Bound in several applications [6] to name a few. The main objective of this paper is to serve as a reference to those researchers and engineers that want to introduce themselves in the field of aperiodic spreading sequences for active sensing. For that purpose, we present a thorough revision of the classical and the novel spreading sequences available in the literature for active sensing, using mathematical formulations only when necessary.

The rest of the paper is organized as follows: in Section 2 we introduce the basic concepts involved in the use of spreading sequences for active sensing. Later, Section 3 presents a classification of spreading sequences and an analysis of their properties, finally in Section 4 we derive the conclusions of this paper.

2. Basic concepts

There are three approaches that can be used to improve the accuracy and robustness of ranging systems: we can optimize the receive filter [7–10], the transmitted signal [11,12], or jointly optimize them [13,14]. In the following paragraphs we will succinctly describe these approaches.

1. Optimization of the receiver filter: To enhance ranging accuracy and immunity to Additive White Gaussian Noise (AWGN), the matched filter is used. This filter maximizes the Signal-to-Noise Ratio (SNR) at its output in the presence of AWGN [7,15,16]. In practice, the matched filter is implemented by correlating the digitized received signal with a template of the transmitted one. Given two complex and unitary sequences of length L, $\{s_n[l],\ s_m[l]\};\ 0 \le l \le L-1$, with $\{s[l]\}$ given by

   $$\{s[l]\} = \{A_l\, e^{j\phi_l}\} = \{A_l[\cos(\phi_l) + j\ \sin\phi_l]\} \tag{1}$$

   the discrete aperiodic correlation function is defined as

   $$C_{s_n,s_m}[\tau] = \begin{cases} \sum\limits_{l=0}^{L-1-\tau} s_n[l]\cdot s_m[l+\tau]^*, & 0 \le \tau \le L-1 \\ \sum\limits_{l=0}^{L-1+\tau} s_n[l-\tau]\cdot s_m[l]^*, & 1-L \le \tau < 0 \\ 0, & |\tau| \ge L \end{cases} \tag{2}$$

   where $s[l]^*$ denotes the complex conjugate of $s[l]$. Eq. (2) represents the aperiodic auto-correlation function when $n=m$ (i.e. the sequences $s_n[l]$ and $s_m[l]$ are matched), and the aperiodic cross-correlation function when $n \ne m$. In the aperiodic correlation function, different periods of the sequence $s[l]$ do not overlap in the correlation process. This is what happens in bursting transmissions, typically used in wireless sensor networks, ultrasonic and UWB ranging systems. This paper is focused on the review of spreading sequences for aperiodic correlation and do not address those designed for periodic correlations, mostly found in wireless communication systems.

   Unfortunately there are other limiting factors than AWGN that prevents the matched filter from being an optimum filter, as fading channels, Inter-Symbol Interference (ISI), Multiple-Access Interference (MAI), or the presence of colored noise to name a few. In the case of having colored noise, the matched filter can be preceded by a weight function (also known as pre-whitening filter) to improve ranging accuracy and immunity to noise. This filter in cascade with the matched filter is commonly named as generalized matched filter or Generalized Cross-Correlation (GCC) function and it has found applications in passive source localization and active ranging estimation [9,10]. There exist other alternatives to deal with the previous limiting factors as the use of the so-called mismatched filters [8,17] (also known as inverse filtering or more recently, Instrumentation Variable filters) for sidelobe suppression [13].

   There are mainly two approaches in the sidelobe suppression with mismatched filters: the first one consists on the use of a mismatched filter alone, designed for a specific transmitted waveform, instead of a matched filter [18,19]; the second approach uses a mismatched filter in cascade with a matched filter [17,20] for removing the cross-correlation sidelobes. Both approaches introduce a SNR loss, as these filters are not optimized for that objective; instead of that, the coefficients of this filter are computed by means of an optimization algorithm, as Least Squares or Iteratively Reweighted Least Squares [21] and it can minimize two merit factors: the Integrated Sidelobe Levels (ISL) or the Peak Sidelobe Levels (PSL) of the correlation (the former one is computationally much more demanding). These algorithms have been also extended to cope with multiuser environments [18] or Doppler shifts [22].
2. Optimization of the transmitted signal: Another way to enhance the accuracy and robustness of ranging estimation is to focus on the optimization of the transmitted signal. In order to improve the performance of