

Techniques for Optimal DSSS Code Selection for SAW Multi-Sensor Systems

Hines, A. T., Tucker, D. Y. G., Hines, J. H.

Applied Sensor Research & Development Corporation
Arnold, MD USA
athines@asrdcorp.com

Castro, J., Abedi, A.

Electrical and Computer Engineering
University of Maine
Orono, ME, USA

Abstract— Direct Sequence Spread Spectrum (DSSS) codes have a variety of applications, including implementing code diversity in wireless surface acoustic wave (SAW) multi-sensor systems. Such systems generally suffer from code collision problems, necessitating complex post-processing to avoid negatively impacting sensor calibration and system accuracy. Thus, development of groups of codes that exhibit very low cross-correlation is desirable to implement code diversity in passive wireless sensor systems. This paper discusses generation and analysis of Gold codes, a known class of codes with desirable cross-correlation properties. A logical criteria-based method for the ‘exhaustive’ analysis of codes of a given length is also presented, applying a selected set of screening techniques to rapidly evaluate all possible candidate codes to a sufficient degree. Using this technique, sets of codes can be found that perform well in asynchronous correlation-based wireless sensor systems, reducing the need for complex post-processing.

I. INTRODUCTION

Direct Sequence Spread Spectrum (DSSS) codes utilize a pseudo random binary sequence (PRBS) with a certain number of bits to phase modulate a sine wave at the signal carrier frequency. Such DSSS coded signals find wide application in communication systems [1], and can be used to implement code diversity in passive wireless SAW multi-sensor systems [2,3]. Historically, such systems have suffered from code collision problems. Interference caused by cross-correlation between codes, particularly in asynchronous systems, introduces an irreducible error signal into the raw data read from each sensor, which can negatively impact sensor calibration and system accuracy unless complex post-processing is used for error correction. Thus, development of groups of codes that exhibit very low cross-correlation is desirable for code diversity in passive wireless sensor systems.

In the interest of minimizing code cross-correlation, one can apply a variety of screening techniques to rapidly evaluate candidate codes. Generation of special classes of codes, such as Gold codes, may be advantageous for large code lengths, where exhaustive evaluation of all possible codes can be time

or memory prohibitive. Alternatively, efficient methods can be developed for extracting desirable codes from all possible codes of a given length. During this code extraction process, one aims to logically eliminate redundancy in codes while retaining codes that exhibit desirable characteristics and interactions with other codes. This paper presents two different approaches to the analysis of sets of codes in a digital environment: generation and analysis of the aforementioned Gold codes; and an ‘exhaustive’ method for the analysis of a set of codes of a given length, covering all possible codes to a sufficient degree, with an emphasis on logical sequencing and reduction mechanics to achieve optimal codesets with reasonable runtime and memory usage.

II. CODESET CONSIDERATIONS

DSSS codes of length N contain N bits (note: the usage of “bit” in this context does not correspond to the usage of this term in information theory). The number of possible binary codes that can be generated for a given code length N is $2^N - 1$, so longer codes generate significantly larger possible sets of codes from which to choose “good” subsets that work together well. A “good” set of codes is defined as a group of codes that all have desirable autocorrelation and cross-correlation properties. A brute force method can be used to evaluate every possible code of length N , although this becomes computationally inefficient for large codes during cross-correlation. Alternatively, families of codes with known properties can be evaluated for use. The authors pursued both of these options during this work. Once a potential “good” codeset was defined, the operation of a selected correlator-based receiver system using this set of codes was simulated to determine the degree to which codes interact when used synchronously and asynchronously.

III. GOLD CODES

It has been shown that quasi-orthogonal Gold codes tend to have high autocorrelation peak to side lobe ratios (PSLR) and low cross-correlation side lobes [1], and that these are desired qualities for the implementation of multiple access for wireless passive surface acoustic wave (SAW) sensors [3].

The authors thank NASA for its support (STTR contract NNX11CI27P).

Fig. 2a shows the system responses of the three receiver matched filters with only the single code 31.1 present. The correlation peak with the code 31.1 filter can be seen at 250 MHz, and the responses of the non-matching filters to code 31.1 are small. Fig. 2b shows the matched filter responses when all three 31-bit codes are present. The presence of all codes together alters the measured response of a single sensor by 10.2% to 32.6%. The presence of all three codes produces high levels of cross-correlation interference that would make sensor identification and measurement difficult. This interference will depend on which codes are present, and on the relative position of each sensor in the group (due to both signal attenuation with sensor distance and difference in code cross-correlation properties with delay offsets). These factors complicate implementation of error correction algorithms for multi-sensor systems with large groups of sensors at random locations relative to the reader. Such algorithms would need to correct for code interference that is large compared to the actual sensor signals of interest. While this can be done in active CDMA systems that utilize handshake mechanisms for synchronization, errors of this sort might be harder to overcome in passive wireless sensor systems. Thus, development of sets of codes that minimize this cross-code interference when used in the sensor system of interest is highly desirable. This motivated ASR&D to develop an alternative code generation and analysis tool.

IV. EXHAUSTIVE CODE EXTRACTION

A. Codeset Generation Technique

ASR&D developed MATLAB based routines capable of generating and analyzing all possible codes of a given length. For a set of codes of a given length (N bits), with two states for each bit producing $2^N - 1$ non-zero variations, evaluation of about half the total number of codes ($2^{(N-1)} - 1$) is sufficient, as the remaining codes will have the same performance as their bit-flipped counterparts in half evaluated. The routines allow the user to specify code length, maximum allowed autocorrelation and cross-correlation sidelobe levels, the maximum number of codes to retain for evaluation at each program step (which can be set to retain all codes found that meet specifications), and other performance parameters. This tool first evaluates the autocorrelation of each possible code, and retains codes that meet autocorrelation performance requirements in a ranked list. This process takes a fixed runtime on a given processor, which increases more than linearly with the code length. If the maximum number of codes to be retained is set to be large (say 50,000 or more) and/or the auto-correlation sidelobe requirements are very strict, the retained list may have fewer codes than requested.

All pairwise cross-correlations are then calculated for the retained codes. Fig. 3 plots the peak cross-correlation values

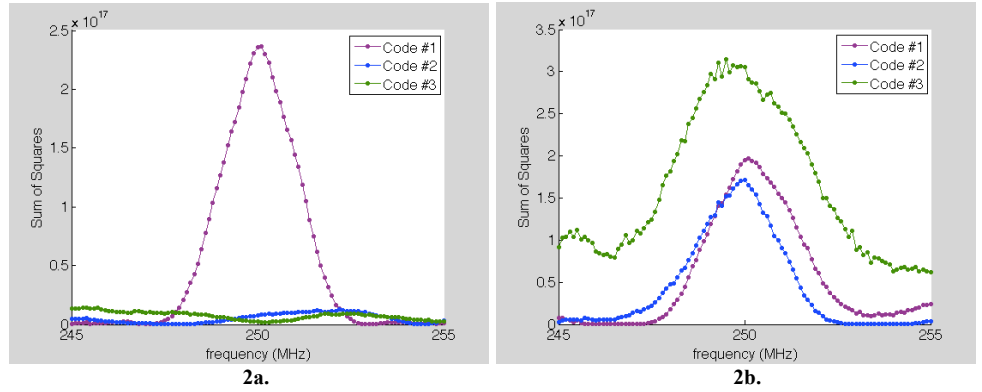


Figure 2: Simulated system response to SAW devices with codes 31.1, 31.2, and 31.3. **2a.** The individual filter responses to the presence of only code 31.1; **2b.** The filter responses to all three codes simultaneously.

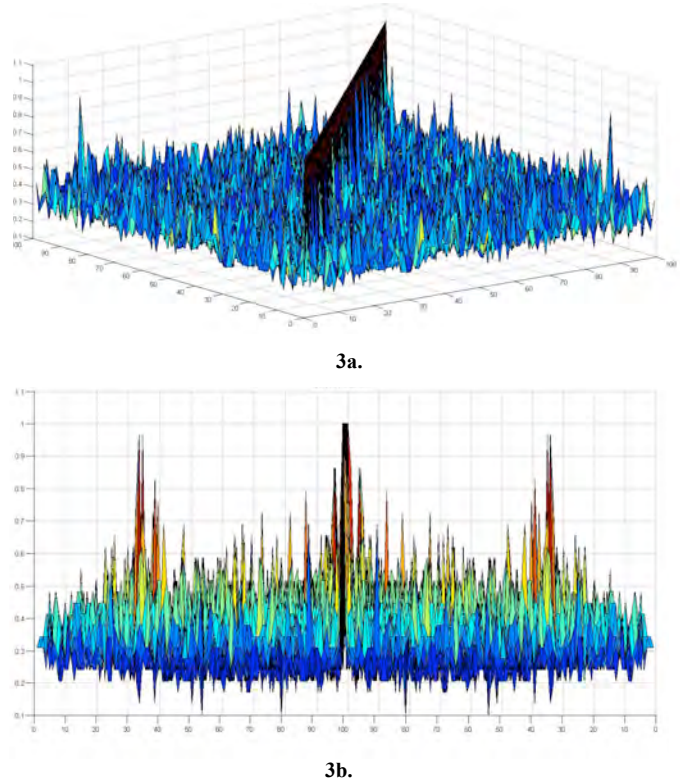


Figure 3: Maximum sidelobe level for cross-correlations of DSSS codes that meet autocorrelation requirements. **3a.** Correlations for a set of 27-bit codes, where peak along diagonal represents code autocorrelations. **3b.** Correlations for a set of 29-bit codes viewed sideways reveal code pairs with very low maximum cross-correlations.

for a set of 27-bit codes that met specific autocorrelation performance goals. Cross-correlation levels are high for many pairs of codes, yet some have desirable properties. Fig. 3b shows several pairs of codes that have maximum cross-correlation levels that are only 10% of the autocorrelation peak. Those that meet the specified cross-correlation goals are once again retained, producing a list of code pairs that meet both auto- and cross-correlation requirements, ranked by autocorrelation performance. From this list, groups of codes can be formed when pairs share common codes. The benefit of this approach is that it provides an exhaustive evaluation of all possible codes of a given length, ensuring

the user that the set of codes identified is the best possible set of codes of that length that meet the target performance parameters. Also, this code is computationally efficient; it allows the user to run multiple passes with different performance specifications to determine if formation of large codesets is possible. ASR&D has used this tool to evaluate codes of lengths ranging from 13 bits to 28 bits.

B. Codeset and System Simulation

Codes generated in this manner were evaluated using the system simulation, as was done for the Gold codes. Fig. 4 shows an example of the correlation properties for three, 28-bit DSSS codes selected using the exhaustive technique that were designed to have zero mutual cross-correlation at the center of the cross-correlation function, which corresponds to the autocorrelation peak. Note that the cross correlations are exactly zero at the center of the autocorrelation peak, and remain at or below 1 over a five bit range around the center. This provides for lower code induced interference, as this signal level is only 1/28 of the correlation peak (or 3.5%).

Evaluating the system response for these three codes, assuming synchronous operation, shows that the level of code interference has been significantly reduced. Fig. 5 shows the system response for these codes implemented as SAW devices at the same delay. Fig. 5a shows the response of the three matched filters when only one code is present (Code #1) while Fig. 5b shows the responses with all three present. Note that the response of the two matched filters for Codes #2 and #3 to the presence of Code #1 is virtually zero across the entire span, substantially lower than in Fig. 2a. Comparing the reader matched filter responses with single codes in the field of view to the responses when all codes are present synchronously indicates an error in the system response amplitude for each code of less than 5.3%. While these errors will still require post-processing to achieve the desired measurement accuracy, they are significantly improved from those of codes with non-zero cross-correlations at the center of the autocorrelation peak [4]. System simulation for these codes showed similar benefits for asynchronous operation.

V. CONCLUSION

Correlation-based passive wireless multi-sensor systems suffer from code-collision induced errors. These errors are exacerbated for systems that utilize sensors that operate asynchronously, due to changes in cross-correlation properties of sensors located with arbitrary RF signal delay offsets due to sensor placement. These errors will affect sensor calibration and measurement accuracy, whether the measured parameter is delay, frequency, phase, amplitude, or another property. A logic-based method has been developed to allow the formation of sets of DSSS codes with auto- and cross-correlation properties that are

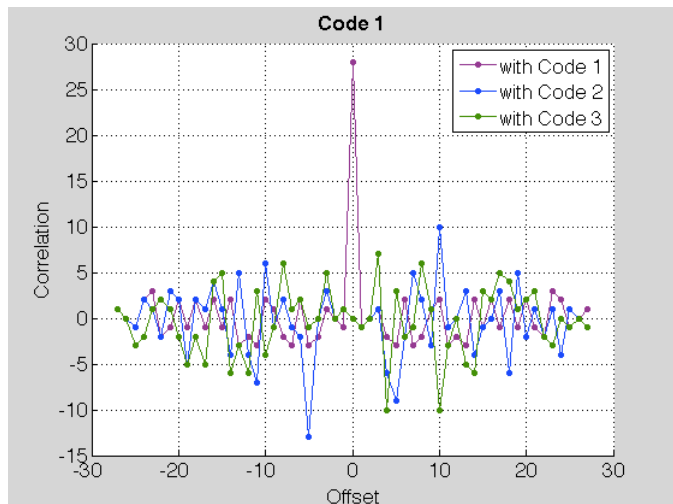


Figure 4: Auto and cross-correlations of three 28-bit DSSS codes found by exhaustive search. The autocorrelation of code 1 is shown along with the crosscorrelations of code 1 with codes 2 and 3. Note that the cross correlations are exactly zero at the center of the autocorrelation peak, and remain at or below 1 over the remainder of the autocorrelation peak.

desirable for minimization of error when used in correlation-based wireless multi-sensor systems. Codes that can be implemented in SAW passive wireless sensors that will produce very low cross-correlation interference over a specified time range around the autocorrelation peak have been identified. Sensors utilizing such codes will exhibit low code-interference induced errors for both synchronous and asynchronous operation in systems with correlation-based transceivers, minimizing errors introduced due to changes in correlation properties with relative delay changes.

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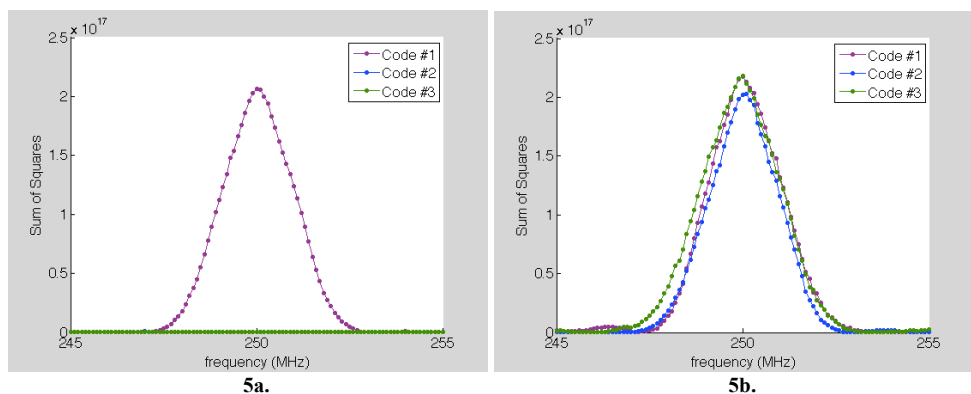


Figure 5: Simulated system response to SAW devices with 28-bit DSSS codes. **5a.** The individual filter responses to the presence of Code #1 only; **5b.** The filter responses to all three codes simultaneously.