Detection Performance of Spread Spectrum Signatures for Passive, Chipless RFID

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***Abstract*—Time-Domain Reflectometry (TDR) RFID tags are passive, chipless tags that use discontinuities along a transmission line to create reflections. The discontinuities may be designed to produce a bipodal signal encoded with the unique identifier of the tag. When multiple tags are co-located and interrogated simultaneously, multiple access interference degrades the ability of the reader to detect the tags accurately. Reader detection can be improved by using spread spectrum signatures as the unique identifiers to limit interference. This work evaluates the ability of Gold codes and Kasami-Large codes to improve detection performance of a passive, chipless TDR RFID system. Simulations were conducted for varying numbers of simultaneously interrogated tags using synthetic tag responses constructed from the measured waveform of a prototype TDR tag. Results indicate that the Gold Code signature set outperforms the Kasami-Large Code signature set and a random, naïve set for simultaneous interrogation of less than 15 tags. For larger numbers of simultaneous tags, a random set performs nearly as well as the Kasami-Large Code set and provides more useful signatures.**

I. Introduction

RFID tags that are both passive and chipless are a topic of great interest due to their low per-unit cost. Chipless RFID tags can be generally classified as time-domain or frequency-domain based tags. Time-Domain Reflectometry (TDR) RFID tags are interrogated by a pulse from the tag reader and encode data in the echoes of the backscatter signal [1]. Frequency-domain tags operate by transforming the frequency spectrum of the interrogation signal to encode bits, usually with resonating elements [2]. Delay-line based TDR tags are particularly attractive due to their ability to be printed directly onto a substrate [3]. However, they present certain challenges that limit their usefulness in environments where multiple tags may be responding simultaneously to a tag reader. Multi-access interference can severely degrade the quality of the received signal and prevent successful tag detection.

Spread spectrum signatures, also known as spreading codes, are presented as a method to mitigate the effect of multi-access interference. Spread spectrum signatures are binary, antipodal codes that allow multiple signals to share a communication channel over the same time and frequency while reducing the effects of narrowband interference [4]. They are in widespread use across a variety of applications including telecommunications [5], radar [6], sonar [7], and GPS [8]. While these techniques are well documented for the aforementioned applications, their use in RFID has been limited. The effort reported here seeks to quantify the utility of spread spectrum signatures in the detection process of passive, chipless RFID.

Two methods for generating signature sets which are prominently used in communication systems have been selected for evaluation in this effort: Gold codes [9] and Kasami-Large (Kasami-L) codes [10]. Gold codes were selected primarily for their good cross-correlation properties while the Kasami-L codes were selected for their relatively large number of available signatures. A random, naïve code was also used as a baseline for comparison.

In this paper, the signature-set generation methods are compared through simulations of simultaneous interrogations. Synthetic tag responses were constructed from the measured waveform of a prototype TDR tag. The performance was assessed via a detection algorithm with a threshold on the maximum cross-correlation. The empirical results of the simulations are presented along with a brief statistical analysis of the set-generation methods. Finally, a series of comparisons are performed for RFID system applications.

II. Spread Spectrum Signature Sets

A. Application to RFID

When an interrogation is initiated in a passive RFID system, all tags within range of the interrogation will respond. The tag responses are multiplexed onto the channel which results in multi-access interference. Spread spectrum signatures can mitigate this interference. In spread spectrum encoding, data are multiplied by a signature that is longer than the encoded data. With respect to passive, chipless RFID, the signature is the identifier of the tag, and the presence of the tag is the encoded data. The reader detects a specific tag by correlating the received signal with the signature of the tag of interest. The correlation operation spreads possible narrowband interference in the received signal over a larger bandwidth, thereby reducing the power of the interference in the recovered signal.

The level of interference due to multi-access between the tag of interest and a concurrent multiplexed tag is proportional to the cross-correlation function of their respective signatures. Interference is reduced by minimizing the absolute value of the cross-correlation between the signatures. In a synchronous system, mutually orthogonal signatures, such as those derived from a Hadamard matrix [11], can be used which have a cross-correlation of zero. In an asynchronous system, it is not possible to guarantee that any two signatures will be mutually orthogonal due to the unknown phase offset. Instead, signatures should be chosen which minimize the cross-correlation between any two signatures in the set with an arbitrary offset. It is expected that reflections from the tags in an RFID system would arrive asynchronously at the receiver, since the tags are not guaranteed be the same distance from the interrogator. The difference in transmission distance creates delay between the tag responses. Furthermore, any combination of the tags may respond to an interrogation, so it is necessary to consider the maximum cross-correlation of all nodes.

B. Signature Set Generation Methods

The Gold Code and Kasami Code signature set generation methods are well established spread spectrum coding techniques that are commonly employed in telecommunications and other fields. These codes were selected for evaluation in an RFID application due to their bounded cross-correlation properties. A randomly generated signature set was used as a naïve approach.

1) Gold codes: A Gold code has bounded, periodic cross-correlation [12]. The maximum cross-correlation of Gold Code signature sets is close to, but does not achieve, the Welch bound [13] which is the theoretical minimum for the maximum cross-correlation of complex-valued signatures. A Gold set can be constructed for signatures with a length of $L = 2^n - 1$ bits, where n is a positive integer [9]. The generated set will contain $L + 2$ unique signatures, thus the number of unique signatures scales linearly with L.

2) Kasami code: Kasami Code signature sets also have bounded, periodic cross-correlation [10]. A Kasami-Small (Kasami-S) Code set can be constructed for signatures with a length of $L = 2^n - 1$ bits, where n is a positive integer and $(n \bmod 4 = 2)$. The generated set will contain $2^{\frac{n}{2}}$ unique signatures. Kasami-S signature sets have a lower maximum cross-correlation than Gold signature sets and are optimal with respective to the Welch bound. The disadvantage of Kasami-S sets is that the number of unique signatures is small, and there are few practical values for L. For these reasons, Kasami-S Codes were not selected here for evaluation, though system designers who can work within its constraints should consider them to attain the best cross-correlation performance.

Kasami-L Codes are an extension of the Kasami-S Codes which yield $2^{\frac{n}{2}}(2^n + 1)$ unique signatures. The trade-off is that the maximum cross-correlation of Kasami-L sets is four times larger than the maximum cross-correlation of Kasami-S sets. The Kasami-L Code was selected for evaluation, because it has $2^{\frac{n}{2}}$ times more signatures than the Gold Code.

3) Random Bipodal Sets: A Random Bipodal signature set contains random signatures chosen from the 2^L signatures available in L bits. This set was included as a baseline for determining the improvements possible with more intelligent coding schemes.

III. Detection Simulation

A simulation was developed in MATLAB to investigate the ability of the spread spectrum signature sets to mitigate the multi-access interference of simultaneously interrogated tags.

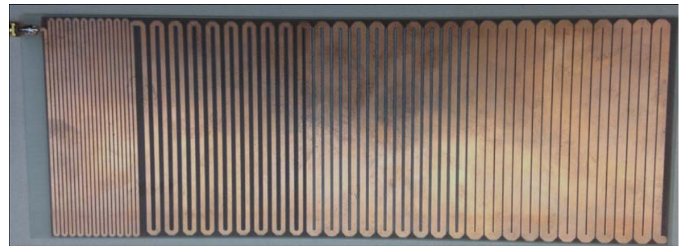

Fig. 1. Prototype TDR tag encoded with three bits, ¡$+1, +1, +1$¿. The encoded bits are created by increasing the width of the microstrip transmission line to produce an impedance mismatch.

A. Signal Construction

The measured waveforms from the impulse response of a 3-bit TDR prototype (Figure 1) were the basis for constructing the simulated tag response. The prototype tag uses impedance mismatches to encode bits by reflecting back a portion of the incident signal. The reflection coefficient (Γ) is the ratio of the amplitude of the reflected signal to the amplitude of the incident signal. The coefficient corresponding to i^{th} bit, Γ_i, is defined as

$$\Gamma_i = \frac{Z_i - Z_{i-1}}{Z_i + Z_{i-1}}, \tag{1}$$

where Z_i is the impedance of the transmission line following the discontinuity and Z_{i-1} is the impedance of the transmission line preceding the discontinuity. The tag in Figure 1 was designed such that $\Gamma_i = 0.1$ at each of the discontinuities. The transmission line has a characteristic impedance of $Z_0 = 50\Omega$ at the connector, so the impedance was increased to $Z_1 = 61.1\Omega$, $Z_2 = 74.7\Omega$, and $Z_3 = 91.3\Omega$ for the three bits.

The impulse response of the tag (shown in Figure 2) was measured using a network analyzer. The three pulses in the waveform correspond to the reflections from the first, second, and third bits. The first pulse was selected to be representative of a "+1" bit on an encoded tag. From Equation 1, a negative Γ will result when $Z_L < Z_S$. A negative Γ produces a phase shift of π in the reflected signal. A "-1" bit can be constructed by negating the voltage level of a "+1" bit, effectively shifting the carrier phase by π, as shown in Figure 3. In simulation, synthetic tag responses were generated by concatenating a series of the "+1" and "-1" bit waveforms according to the signature associated with a specific tag.

B. Simulation Description

Three signature sets were generated with $L = 63$, one for each of the construction methods described in Section II. An ideal channel (i.e., no fading or multipath) was considered in order to focus on the effects of the multi-access interference. 5000 trials were executed for each combination of signature set and number of simultaneously interrogated tags. For each trial, between 2 and 40 signatures were randomly selected without replacement. The selection of a signature represents the presence of the RFID tag with that unique identifier.

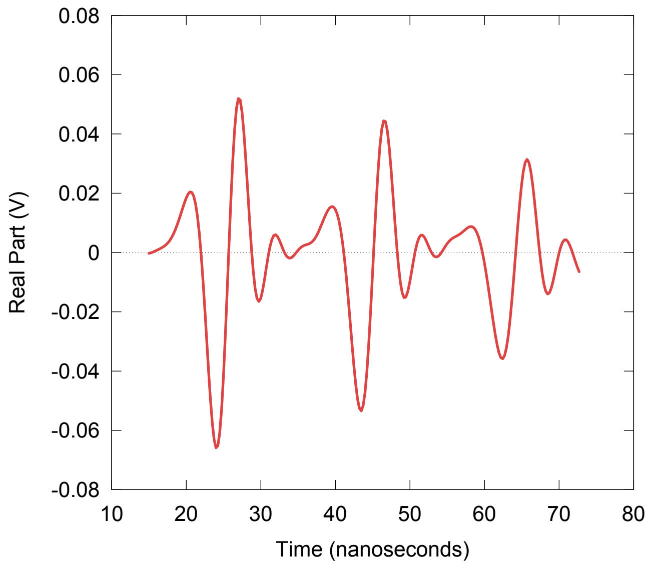

Fig. 2. Real part of the impulse response of the encoded TDR prototype tag.

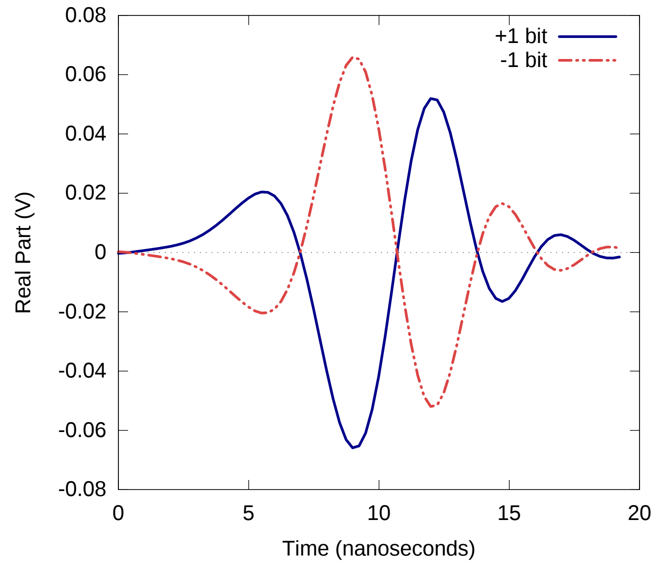

Fig. 3. The $+1$ and -1 bit waveforms used to construct the simulated tag response.

Time domain impulse responses were created via the process described in Section III-A.

It was assumed that future passive, chipless RFID systems will have a range of at least 3 meters. Accordingly, each simulated response was delayed by a uniformly random time up to the period of one bit (i.e. 10 ns, the time required for electromagnetic radiation to travel 3 meters).

The simultaneous interrogation was mimicked by summing all of the randomly selected and delayed responses. The combined response was then correlated against every signature in the set. The maximum cross-correlation values were compared against a moving threshold in order to develop the Receiver-Operating-Characteristic (ROC) Curve.

C. Performance Metric

The ROC curve serves as the benchmark for detection performance. It shows the relationship between the True Positive Rate and the False Positive Rate of a binary classifier. Each signature in the set was classified as present or not present based on a threshold of the maximum cross-correlation between the combined response and that signature. A tag was considered to be present if the maximum cross-correlation of its signature with the received signal was above the threshold whereas the tag was considered not present if the maximum cross-correlation was below the threshold. The curve is generated by varying the threshold from the minimum of all cross-correlation values to the maximum of all cross-correlation values. Tags that were present and correctly labeled as present were counted as true positives, while tags that were not present yet still labeled as present were counted as false positives. The theoretical best performance is a true positive rate of 1 with a false positive rate of 0. The worst performance is when the true positive rate is equal to a false positive rate, which is equivalent to randomly guessing if a tag is present or not.

TABLE I
PROPERTIES OF SIGNATURE SETS WITH $L = 63$.

Signature Set	Number of Unique Signatures	Maximum Cross-Corr.	Mean Cross-Corr.
Gold	65	0.3810	0.0625
Kasami-L	520	0.3810	0.0667
Random Bipodal	2^{63}	0.9841	0.4008

IV. RESULTS

A. Signature Set Statistics

Signature sets with $L = 63$ were generated for each of the three set generation methods described in Section II. A statistical analysis of the aperiodic cross-correlation of these sets is shown in Table I. For this signature length, the Gold code set and the Kasami-L code set have similar maximum cross-correlation, though Gold sets have a smaller mean. The trade-off is that the Kasami-L code set provides nearly 10 times more unique signatures. Both the Gold code set and the Kasami-L code set have lower maximum and mean cross-correlations than the Random Bipodal set. From these observations, it is expected that Gold sets will have the lowest multi-access interference and the best performance.

B. Detection Performance

A sample of the generated ROC curves is presented in Figures 4-7. It represents the overall performance of the signature set generation methods. The codes had nearly perfect detection between two and seven tags. After eight tags (Figure 4), the Gold Code has an advantage on the Kasami-L Code and the Random Bipodal set. The Gold Code maintains good performance even as the Kasami-L Code and the Random Bipodal set begin to degrade as the number of simultaneous tags increase, as shown for 15 tags in Figure 5. The Gold

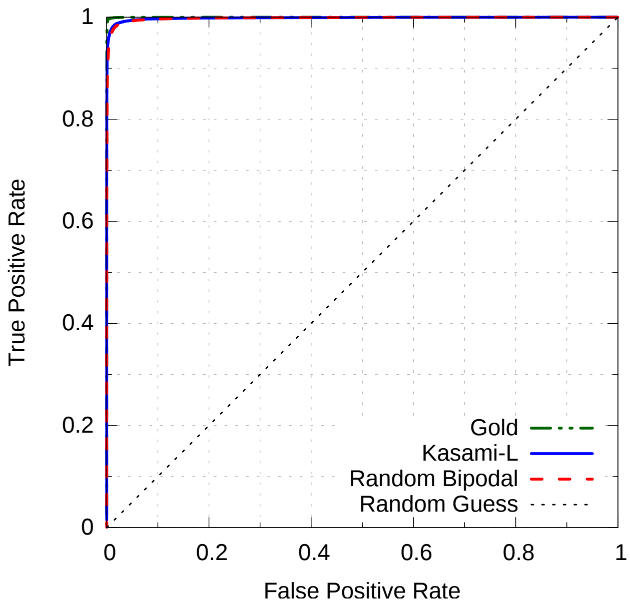

Fig. 4. ROC Curve for simultaneous interrogation of 8 tags.

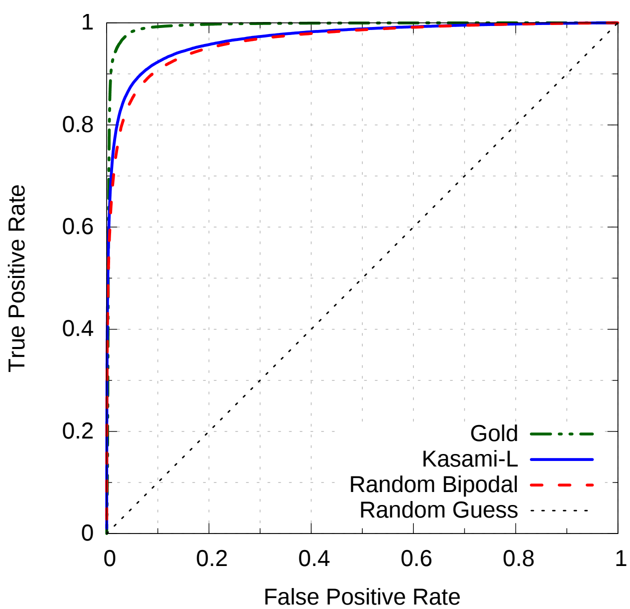

Fig. 5. ROC Curve for simultaneous interrogation of 15 tags.

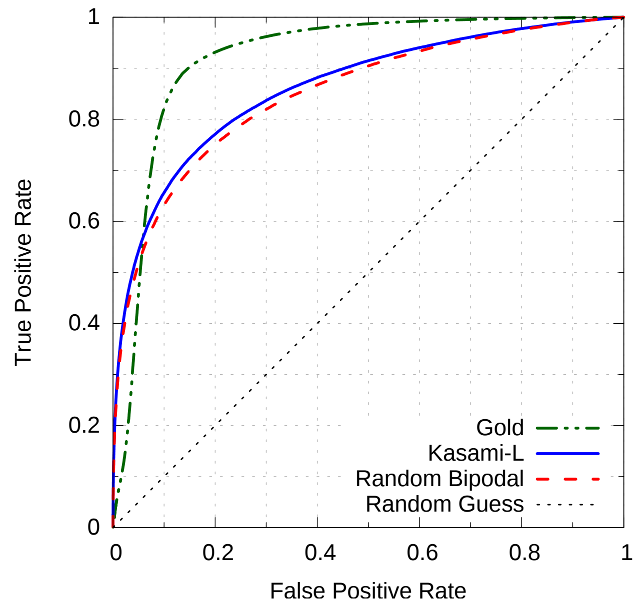

Fig. 6. ROC Curve for simultaneous interrogation of 25 tags.

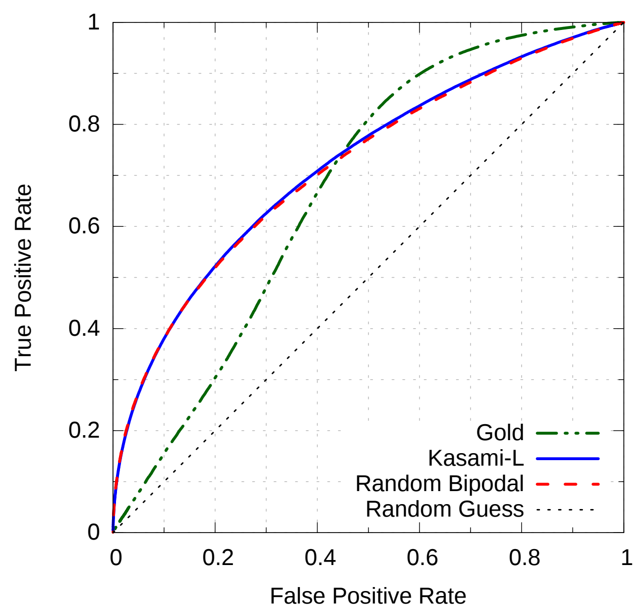

Fig. 7. ROC Curve for simultaneous interrogation of 40 tags.

code set outperforms because it has the lowest, average cross-correlation of the three sets.

For 25 tags (Figure 6), an interesting trend emerges where the true positive rate of the Gold code set decreases dramatically for low false positive rates. It is only able to outperform the Kasami-L code set and the Random Bipodal set once the false positive rate surpasses 0.06. The drop in performance is caused by the Gold code using more than a third of the total available signatures in the set. When using a large fraction of the available signatures, there is a greater likelihood that the selected subset of signatures contains pairs of signatures with high cross-correlation. With 40 tags (Figure 7), the effect is even greater. The Kasami-L code set and the Random Bipodal set do not exhibit this same phenomenon as the Gold Code does due to the Kasami-L code set and the Random Bipodal set using a smaller fraction of their available signatures.

When the number of simultaneous tags was increased to the maximum number possible for a Gold code set with $L = 63$ (65 tags), the performance of the Gold code set degraded to the worst case scenario (the same as a random guess).

The Kasami-L code set performed slightly better than the Random Bipodal set. However, the Random Bipodal Set provided a much larger number of useful signatures.

V. Conclusion

When many co-located tags are interrogated simultaneously, the performance of passive, chipless RFID systems suffers from multi-access interference. Spread spectrum signatures were presented as a method of mitigating this interference. The Gold code and the Kasami-L code sets were selected for evaluation and compared to a random, naïve set. To assess the detection performance of these codes, a simulation was developed which interrogated synthetic tag responses. The synthetic tag responses were constructed from the concatenation of the measured waveform of a prototype TDR tag. ROC curves were developed by varying a threshold on the maximum cross-correlation of the received signal.

For a low number of simultaneous tags (less than 8), the detection was nearly perfect for all of the sets. Between 8 and 15 tags, the Gold code set had a notably better performance than both the Kasami-L code set and Random Bipodal set. For 25 tags, the detection rate for the Gold code set dropped dramatically due to the increasing fraction of used signatures in the set. The Kasami-L code set and the Random Bipodal set had improved detection over the Gold code set for more than 25 tags. The Random Bipodal set performed nearly as well as the Kasami-L code, while providing a larger number of useful signatures. For signatures with a length of 63 bits, it is recommended that Gold codes be used for simultaneous interrogation of 15 tags or fewer. For more than 15 simultaneous tags, either Kasami-L codes or a Random Bipodal set can be used.

The results also indicate that the detection performance of all sets sharply declines as the number of simultaneously interrogated tags exceeds 40 tags for signatures with a length of 63 bits. Longer signatures (i.e., more than 63 bits) would extend the benefits of spread spectrum signatures past this limit. Other methods (e.g., time-gating, beam-steering, etc.) could also be deployed in conjunction with spread spectrum signatures to improve detection even further. These benefits make spread spectrum signatures an attractive option for passive, chipless RFID systems.

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