Dynamic Bit Encoding for Privacy Protection Against Correlation Attacks in RFID Backward Channel

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Abstract—Nowadays Radio Frequency Identification (RFID) technologies are applied in many fields for a variety of applications. Though bringing great productivity gains, RFID systems may cause new security and privacy threats to individuals or organizations. Therefore, it is important to protect the security of RFID systems and the privacy of RFID tag owners. Unfortunately, none of the existing solutions provide a complete defense against eavesdroppers who could monitor the communication between RFID readers and tags and recover the contents of tags. Based on our research, we propose two novel RFID backward channel protection protocols, namely dynamic bit encoding and optimized dynamic bit encoding. Our schemes are able to achieve high anonymity with limited communication overhead. Our extensive simulations show that both proposed schemes provide much stronger backward channel protection than existing techniques. In addition, analytical models were created and validated through comparisons with simulation results.

Index Terms—Radio Frequency Identification, RFID, privacy protection, bit encoding.

1 INTRODUCTION

Radio Frequency Identification (RFID) is an electronic tagging technology that allows objects to be automatically identified at a distance without a direct line-of-sight using an electromagnetic challenge-and-response exchange of data [29]. RFID systems smooth the way for various applications such as supply chain management [17], [24], transportation payment, animal identification, warehouse operations [5], and more. Though bringing great productivity gains, RFID systems may cause new security and privacy threats to individuals or organizations [9], [14], [22], [28]. In all the aforementioned applications, an RFID reader has to identify individual tag IDs within its reading range. When a reader queries for tag IDs, several tags may respond at the same time and this would result in signal collisions. Several anti-collision protocols have been proposed [8], [21], [30] and the binary tree-walking-based scheme is commonly used. With the binary tree-walking-based protocol, a reader broadcasts each bit of the singulated tag’s ID over the long-range forward channel, and eavesdroppers who are within the signal range of the reader can monitor the process and recover the contents of every tag. In order to protect privacy, a number of techniques [30], [31] have been designed to safeguard the forward channel in RFID systems.

The backward channel – transmitting data from a tag to the reader – has much lower signal energy than the forward channel and is therefore more difficult to observe. However, an attacker could be in close proximity of a tag and s/he may listen to the communication of the backward channel. This will also threaten the privacy of the tag owner. For example, assume a retail store installs an RFID-based smart shelf system for managing RFID-tagged products. In such a setting, an attacker (e.g., a corporate spy from a competitor store) could collect the entire store’s inventory and sales data by pretending to be a customer, if the smart shelf system has no backward channel protection against eavesdropping. Therefore, it is equally important to protect the backward channel. The solution proposed in [3] relies on the reader to transmit a mask bit string concurrently with a tag sending out its identifier through the backward channel. This will result in signal collisions and partially obstructed readings. Since the reader knows the mask bit string, the RFID tag can be successfully reconstructed. Nevertheless, this method suffers from the same bit problem, in which some bits of the tag ID could still be disclosed. An improved solution based on [3] is presented in [18] by encoding each source bit of the tag into a fixed length n-bit string to alleviate the same bit problem. This solution is still vulnerable if an attacker has knowledge of the n-bit string length and can interrogate a tag repeatedly (detailed in the Motivations subsection of Section 3). Consequently, we need more advanced techniques that provide much stronger RFID backward channel privacy preserving capabilities than existing solutions.

In this paper we put forth two novel RFID backward channel
protection protocols. The contributions of this research are as follows.

- We propose a bit encoding scheme, namely Dynamic Bit Encoding (DBE) for privacy protection in RFID backward channels. DBE encodes the $i$-th source bit based on all the preceding $(i-1)$ source bits, which makes it very difficult to crack the original ID.
- We further improve the degree of security of DBE and design an Optimized Dynamic Bit Encoding (ODBDE) scheme by dynamically changing the maximum codeword length for each source bit.
- Analytical models of guessing attacks [18], anonymity against generated encoded ID and correlation attacks are created and validated.
- Analyses for the communication overhead and time complexity incurred by DBE and ODBE are conducted.
- We evaluate our proposed techniques through extensive simulations. The results show that our DBE and ODBE schemes provide a much more robust backward channel protection than previous techniques with the same communication overhead.

The rest of this paper is organized as follows. Section 2 surveys related works. The DBE and ODBE schemes are introduced in Section 3. Analytical models are provided in Section 4. Section 5 presents the analysis for control overhead. The experimental validations of our protocols are presented in Section 6. Section 7 concludes the paper with a discussion of future work.

2 RELATED WORK

In this section we review RFID singulation protocols and previous work related to our approach of RFID system backward channel protection.

2.1 RFID Singulation Protocols

In RFID systems, a reader has to recognize individual tag IDs in its reading region. However, collisions may happen when several tags respond simultaneously to the reader query. Therefore, we need anti-collision singulation schemes for a reader to effectively identify tags in its proximity. Current singulation protocols can be roughly categorized into Aloha scheme based protocols and tree-walking scheme based protocols.

In Aloha-based protocols [8], [20] – named after an early wireless network protocol developed at the University of Hawaii – a reader sends a query frame and each tag randomly chooses a time slot to send its ID information. If more than two tags select the same slot, collisions occur. The colliding tags have to choose another slot to send a response. In addition, the reader can adjust the frame size according to the number of collisions in the previous frame. Although Aloha-based protocols avoid collisions to identify tags, a specific tag may not be identified for a long time – this scenario is also called the tag starvation problem.

In tree-walking-based protocols [21], [25], [31], a reader traverses a binary tag tree, which organizes the entire ID space of tags and each tag ID is mapped to a leaf node in depth-first or breadth-first order. For singulation, a reader broadcasts a query to all tags in the vicinity for the next bit of their ID. On receiving a query, a tag responds if its ID matches the prefix of the bit string in the query. If more than one tag responds, the reader will be able to detect the collision. Afterward the reader will broadcast a bit indicating whether tags who replied with a 0 or those who replied with a 1 should continue. By applying this mechanism, all tags in the interrogation area will be identified. While tree-walking-based protocols may incur a long singulation delay, they do not suffer from the tag starvation problem that occurs with Aloha-based protocols.

Both Aloha and tree-walking-based protocols can be implemented with simple methods such as randomly selecting a time slot and matching query bits with tag IDs to identify low-cost RFID tags. However, all the aforementioned singulation protocols do not support privacy protection of the communication between readers and tags.

2.2 Encryption-based Authentication in RFID

As passive tags are computationally weak devices, they cannot perform traditional cryptographic techniques such as symmetric key and public/private key operations. This enforces a number of authentication solutions for RFID systems to use low-cost cryptographic operations [13]. The basic idea of encryption-based authentication techniques employed in RFID systems works as follow: Assume a reader and a tag share a common secret key, say key $K$, which is a $m$-bit random string. When the tag sends its real ID, it calculates $ID \oplus K$, where $\oplus$ is the XOR operation. The reader decodes the cipher text with the key, and it successfully reads the tag without being eavesdropped. This leads many studies to emphasize on secure key exchange and distributions [7], [15], [19]. However, key-searching and key-updating operations are usually expensive in large-scale RFID systems. In this paper, we focus on tag authentication without a shared secret key between a reader and a tag. The most related works to this paper are reviewed in the following subsection.

2.3 Privacy Protection in RFID Singulation

Since every bit of every singulated tag is broadcast by the reader on the forward channel, attackers could monitor these transmissions from a significant distance and recover the contents of every tag. Weis [30] proposed two secure tree-walking protocols for protecting the forward channel from eavesdroppers. In the blinded tree-walking algorithm [31], when there is no collision in a certain bit position, instead of specifying which portion of the tag population should proceed, readers send the query signal for the next ID bit directly, hence not all the bits are transmitted on the forward channel. In the randomized tree-walking algorithm, each tag has two IDs – a real one and a pseudo-ID allocated by manufacturers or generated by the tag itself. Readers singulate with pseudo-ID values and tags respond with their real IDs over the backward channel.

Eavesdroppers may appear near an RFID tag and clandestinely listen on the backward channel, i.e., the signals sent from a tag to a reader, which leads to privacy threats. Choi
3 System Design

In this paper, we adopt the architecture in [18] and assume the deployment of TMDs. In addition, we assume that each tag takes part in the singulation process with a randomly generated pseudo ID. Based on these assumptions, we propose two novel bit encoding schemes for the purpose of privacy masking to protect the backward channel, namely Dynamic Bit Encoding (DBE) and Optimized Dynamic Bit Encoding (ODBE). The notations used in this paper are listed in Table 1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>The constant length of an encoded ID</td>
</tr>
<tr>
<td>n</td>
<td>The length of a codeword</td>
</tr>
<tr>
<td>b_i</td>
<td>The i-th source bit</td>
</tr>
<tr>
<td>n_i</td>
<td>The number of bits for encoding the i-th source bit</td>
</tr>
<tr>
<td>N_max</td>
<td>The maximum value of n</td>
</tr>
<tr>
<td>N_i</td>
<td>N_max for the i-th bit</td>
</tr>
<tr>
<td>E(i, n)</td>
<td>The codeword of b with length n</td>
</tr>
<tr>
<td>F(key)</td>
<td>A hash function</td>
</tr>
<tr>
<td>P</td>
<td>The correct guess probability</td>
</tr>
<tr>
<td>l</td>
<td>The length of a tag ID</td>
</tr>
<tr>
<td>l_c</td>
<td>The number of unreadable bits</td>
</tr>
<tr>
<td>pr_i</td>
<td>The probability of the i-th bit is identifiable</td>
</tr>
<tr>
<td>φ</td>
<td>The set of all possible IDs</td>
</tr>
<tr>
<td>φ'</td>
<td>The anonymous set</td>
</tr>
<tr>
<td>H_φ</td>
<td>The entropy of the system φ</td>
</tr>
<tr>
<td>d_φ</td>
<td>The degree of anonymity</td>
</tr>
<tr>
<td>R</td>
<td>The number of readable bits</td>
</tr>
<tr>
<td>l_rate</td>
<td>Information rate to measure the effectiveness of coding schemes</td>
</tr>
<tr>
<td>S_l</td>
<td>The set of possible real tag IDs, i.e., {0, 1}^l</td>
</tr>
<tr>
<td>l_{tx}</td>
<td>The length of transmitted IDs (a real or pseudo ID)</td>
</tr>
<tr>
<td>l_p</td>
<td>The length of prefix in tree-walking singulation</td>
</tr>
<tr>
<td>s</td>
<td>The number of slots in Aloha-based singulation</td>
</tr>
<tr>
<td>T</td>
<td>The number of RF tags in the system</td>
</tr>
</tbody>
</table>

3.1 Motivations

To protect the privacy of an RFID tag, a protocol should incur a low probability that the original ID is identified (in the rest of the manuscript we will call this value the correct guess probability and denote it with \( P \)). Ideally, none of the bits in the original ID should be readable by attackers, i.e., all bits in...
the ID or encoded ID should collide with the mask. In such a case the attackers achieve the lowest correct guess probability. When a bit is not readable, the correct guess for the bit has a chance of 50%. Let \( l \) be the ID length and \( l_c \) be the number of unreadable bits. In the best case, \( l = l_c \) and \( P = \left( \frac{1}{2} \right)^l \). On the other hand, when a mask has the same bit sequence as the ID or the encoded ID, the correct guess probability is 100% (i.e., the same bit problem). Thus, we can establish upper and lower bounds for \( P \): \( \left( \frac{1}{2} \right)^l \leq P \leq 1.0 \).

In [3], the probability that each bit collides is 0.5. When a bit collides, the probability that an attacker can identify the source bit is 0.5. On the other hand, if a bit does not collide, the probability is 1. Therefore, the correct guess for the privacy masking protocol without encoding is as follows.

\[
P = \left( \frac{1}{2} \cdot 1 + \frac{1}{2} \cdot \frac{1}{2} \right)^l = \left( \frac{3}{4} \right)^l
\]

For the randomized bit encoding (RBE) scheme [18], the probability that all bits in a codeword do not collide with the mask bit string is \( \frac{1}{2^n} \) with the optimal \( n \)-bit encoding. The probability that a bit is identifiable is \( \frac{1}{2^n} + (1 - \frac{1}{2^n}) \cdot \frac{1}{2} \). Therefore, the correct guess probability of the RBE scheme is:

\[
P(n) = \left\{ \frac{1}{2^n} + (1 - \frac{1}{2^n}) \cdot \frac{1}{2} \right\}^l, \quad (n \geq 1)
\]

Both the privacy masking and RBE protocols provide protection for the backward channel against guessing attacks to identify the original ID. However, after a number of interrogation cycles, attackers can obtain the original ID from collected source bits – this is called the correlation attack of encoded IDs (termed correlation attack for the rest of this paper). As demonstrated in Figure 3, an attacker is able to receive encoded IDs by interrogating the tag repeatedly. The original ID ‘101’ can be identified by decoding the readable codewords of collided IDs received in all the previous cycles. Unfortunately, the two aforementioned protocols are vulnerable to the correlation attack (the analysis is provided in Section 4). To deal with the correlation attack, a stronger tag ID encoding mechanism must be designed.

Fig. 2. Randomized bit encoding with a trusted masking device.

3.2 Dynamic Bit Encoding Scheme

In the randomized bit encoding scheme [18], the encoding of a source bit does not depend on any other bits in the ID. In other words, a source bit can be identified independently. Our fundamental idea is that the codeword to encode the \( i \)-th source bit should be determined based on all the preceding \((i-1)\) source bits. By employing this design, the \( i \)-th bit of the original ID cannot be identified until all the previous \((i-1)\) bits are identified.

In dynamic bit encoding, the source bits in the original ID are encoded by codewords of variable length \( n \) where \( n \in \{1, 2, ..., N_{max}\} \). Let \( b_i \) be the \( i \)-th bit in the original ID, and \( n_i \) be the value of \( n \) for the \( i \)-th bit. The first bit \( b_1 \) is always encoded by a codeword of length \( N_{max} \), and the codeword of \( b_i \) is denoted by \( E(b_i, n_i) \) where \( E(b_i, n_i) \in \{0, 1\}^{n_i} \). If the Hamming weight of the first \( i \) bits is odd, \( E(b_i, n_i) \) returns a bit string whose Hamming weight is odd. Otherwise, it returns a bit string whose Hamming weight is even. For example, if the Hamming weight of the first \( i \) bits is odd, \( E(b_i, 3) \in \{001, 010, 100, 111\} \), and \( E(b_i, 3) \in \{000, 011, 110, 101\} \), if the Hamming weight is even. A tag randomly picks one of the codewords in the set. By applying this design, if one of the codeword bits collides with a mask bit, the corresponding source bit is unidentifiable. In addition, the codeword length of the \( i \)-th bit (except \( b_1 \)) is determined by the result of a

Fig. 3. The correlation attack of an encoded ID.
hash function, $F(key) \in \{1, 2, ..., N_{max}\}$. The key needs to be associated with the codeword of the previous bit to achieve our design goal, and the length of the codeword for the $i$-th bit is $F(E(b_{i-1}, n_{i-1}))$. Most well-known deterministic hash methods can be used for this system as long as they return values uniformly in the range of 1 to $N_{max}$. Consequently, the codeword length of $b_2$ is $F(E(b_1, n_1))$ bits. By repeating these steps, all the bits in the original ID can be encoded.

After encoding all the source bits, the number of bits of the corresponding encoded ID is $\sum_{k=1}^{l} n_k$. We concatenate an extra $l \cdot N_{max} - \sum_{k=1}^{l} n_k$ bits to the end of the encoded ID to pad it to a constant length $C$. Accordingly, the overhead of this protocol is $l \cdot N_{max} - l$. There are two main reasons to append extra bits to the encoded ID to make it $l \cdot N_{max}$ bits long. The first is to improve privacy protection. For example, assume that the length of an encoded ID is $N_{max} + l - 1$ (i.e., the first bit is encoded by $N_{max}$ bits and other bits are encoded with 1 bit) and the original ID is 1011 with $N_{max} = 3$. The encoded ID could be ‘100011’. An attacker with background knowledge is able to infer that the first bit is encoded by 3 bits, and other bits are encoded by 1 bit from the length of the encoded ID. The second reason is that it simplifies TMD, so that the length of the first 2 bits, i.e., ‘10’ is odd, the Hamming weight of the first 2 bits is 2. Since the Hamming weight of ‘111’ is odd, it can find $E(b_1, 3) = 111$. Since the Hamming weight of ‘111’ is odd, the reader obtains $b_1 = 1$. By computing the hash function, the reader acquires $n_2 = 2$. Because the Hamming weight of $E(b_2, 2) = 01$ is odd, the Hamming weight of the first 2 bits (i.e., ‘1X’) has to be odd. As we already know $b_1 = 1$, the reader derives $b_2 = 0$. By repeating this process, the reader can retrieve the original ID of the tag.

3.4 Optimized Dynamic Bit Encoding

To further improve the degree of security for RFID backward channel protection, an Optimized Dynamic Bit Encoding (ODBE) scheme was designed based on DBE. In ODBE, the value of $N_{max}$ is dynamically changed for each source bit. Let $N_i$ be the value of $N_{max}$ for the $i$-th bit. With a randomly generated value for $n$, the length of the first codeword is decided by $n_1 = n$. Then the length of the $i$-th codeword is decided by $F(key) = key \mod N_i + 1$, where $N_i = n \cdot i - \sum_{k=1}^{i-1} n_k$. For the last source bit, its codeword should use all the remaining bits $l_i$ in the encoded ID after $(i-1)$ source bits in the original ID were encoded. The value of $l_i$ can be obtained as follows:

$$l_i = n \cdot i - \sum_{k=1}^{i-1} n_k$$

(3)

The last bit is encoded by a codeword with length $n_i = l_i$. Consequently, the length of the encoded ID is always $n \cdot l$ bits. An example of ODBE is shown in Figure 5 with $n_3 = 3$. ODBE provides a higher degree of security than DBE, which is postulated in the following lemma:

**Lemma 1** When the randomly generated first codeword length $n$ in ODBE is equal to $N_{max}$ in DBE, ODBE results either in lower or equal correct guess probability than DBE.

**Proof:** To prove the above claim, we show that the average value of codeword length for ODBE, $\pi$ is greater than or equal to that of DBE. Let $\pi_i$ be the average value of codeword length for the $i$-th bit in ODBE defined by:

$$\pi_i = \left\{ \begin{array}{ll} \frac{n}{2n_i - \frac{i}{2}} & \text{(if } i = 1) \\ \frac{n}{2n_i - \frac{i}{2}} & \text{(if } i > 1) \end{array} \right. \quad (4)$$

The average value of codeword length of ODBE is:

$$\pi = \left\{ \begin{array}{ll} \frac{1}{2} \sum_{i=1}^{l} \pi_i & \text{(if } i \text{ is small)} \\ \frac{2}{3} n & \text{(if } i \text{ is sufficiently large)} \end{array} \right. \quad (5)$$

Note that $\frac{2}{3} n$ is the lower bound of $\pi$ in Equation 5.
On the other hand, the average value of codeword length for the $i$-th bit in DBE is:

$$\sum_{k=1}^{N_{\text{max}}} k = \frac{1}{2} N_{\text{max}} = \frac{1}{2} n \quad (6)$$

Therefore, the average value of codeword length for ODBe is larger than that for DBE. This concludes the proof.

![Fig. 5. An example of ODBe.](image)

3.5 Implementation Considerations

The privacy masking scheme proposed by Choi and Roh [3], [4] is designed for a tree-walking-based protocol under the assumption that the bit-timing between a tag ID and a mask is properly synchronized. The bit timing synchronization required by this scheme can be realized by the adaptive demodulation of RFID receivers [11]. The fast synchronization in [11] is achieved by demodulating the burst-receiving data and decoding with fewer frequency deviation.

Privacy masking techniques can be implemented not only in tree-walking-based protocols, but also in Aloha-based protocols [8], [20]. In an Aloha-based singulation process, a tag randomly selects a time slot and sends a random number. It then waits for an acknowledgement from the reader. With this handshake, the reader and the tag agree on a time slot during which the pseudo ID is transmitted. Thus, all bits of the pseudo ID and the mask can be synchronized with each other.

The proposed DBE and ODBe protocols do not assume the underlying singulation scheme. In other words, our protocols can be applied to both tree-walking and Aloha-based singulation protocols.

3.6 Privacy Protection with CRC

Cyclic Redundancy Codes (CRC) are commonly used to correct unreadable bits due to communication errors. With CRC, if some of the bits in a data frame are corrupted, the whole frame can be recovered. The use of CRC improves the performance and robustness of communications. However, bit error corrections may lead to lower security. Backward channel protection with CRC has been extensively studied in [4]. The numerical results show that the probability of successfully eavesdropping increases when CRC is employed. Furthermore, CRC introduces extra control and communication overhead. Therefore, we do not consider the application of CRC in this paper.

4 Privacy Protection Analysis

In this section, analytical models of privacy protection are created for both DBE and ODBe.

4.1 Correct Guess Probability

First we analyze the correct guess, which is the probability of an attacker to guess the original ID. For the DBE scheme, the codeword length is among \{1, 2, ..., $N_{\text{max}}$\} and the average codeword length is defined by Equation 6.

Note that from Equation 6, DBE has a higher codeword length than RBE, since the probability is higher than $\frac{1}{2^n}$ when $n = N_{\text{max}}$. However, DBE is less vulnerable to the guessing attack because an attacker has to identify the preceding $(i-1)$ bits to recover the $i$-th bit. If an attacker knows $N_{\text{max}}$, given a DBE-encoded pseudo ID, the probability that exactly the first $i$ bits of the original ID are identifiable (denoted as $pr_i$) is:

$$pr_i(N_{\text{max}}) = \begin{cases} 1 - \frac{1}{2N_{\text{max}}} & \text{(if } i = 0) \\ \frac{1}{2^{N_{\text{max}}}} \cdot \left(\frac{1}{2^{N_{\text{max}}/2}}\right)^{-1} \cdot \left\{1 - \frac{1}{2N_{\text{max}}/2}\right\} & \text{(if } i \geq 1) \end{cases}$$  

(7)

When $i$ number of source bits are disclosed to the attacker, the remaining $(l-i)$ source bits can be guessed with a 50% chance of correctness for each bit. The correct guess of the original ID when $i$ source bits are identified can be denoted by:

$$pr_i(n) = \begin{cases} 1 - \frac{1}{2^n} & \text{(if } i = 0) \\ \left(\frac{1}{2^n}\right) \cdot \left(\frac{1}{2^n}\right)^{i-1} \cdot \left\{1 - \frac{1}{2^n}\right\} & \text{(if } i \geq 1) \end{cases} \quad (8)$$

Consequently, by combining Equations 7 and 8 the correct guess probability of the original ID is:

$$P(N_{\text{max}}) = \left(1 - \frac{1}{2N_{\text{max}}}\right) \cdot \left(\frac{1}{2}\right)^i + \sum_{i=1}^{l} \left(\frac{1}{2^{N_{\text{max}}}}\right) \cdot \left(\frac{1}{2^{N_{\text{max}}/2}}\right)^{-1} \cdot \left\{1 - \frac{1}{2^{N_{\text{max}}/2}}\right\} \cdot \left(\frac{1}{2}\right)^{i-1} \quad (9)$$

For ODBe, $pr_i$ is defined by Equation 10,

$$pr_i(n) = \begin{cases} 1 - \frac{1}{2^n} & \text{(if } i = 0) \\ \left(\frac{1}{2^n}\right) \cdot \left(\frac{1}{2^n}\right)^{i-1} \cdot \left\{1 - \frac{1}{2^n}\right\} & \text{(if } i \geq 1) \end{cases} \quad (10)$$

Note that the average value of the codeword length for ODBe $\pi$ is defined by Equation 5.

Therefore, the correct guess probability can be obtained as shown in Equation 11.

$$P(n) = \left(1 - \frac{1}{2^n}\right) \cdot \left(\frac{1}{2}\right)^i + \sum_{i=1}^{l} \left(\frac{1}{2^n}\right) \cdot \left(\frac{1}{2^n}\right)^{i-1} \cdot \left\{1 - \frac{1}{2^n}\right\} \cdot \left(\frac{1}{2}\right)^{i-1} \quad (11)$$

Figure 6 demonstrates the analytical results of the correct guess probability as a function of different $n$ values; here $n = N_{\text{max}}$. The correct guess is lower-bounded when the all bits are not readable, i.e., $(\frac{1}{2})^i$. As the value of $n$ increases, the correct guess probability decreases for all the solutions. When
n ≥ 7, the correct guess probabilities of DBE, ODBE and RBE are all very close to the lower bound. When n is between 2 and 6, DBE and ODBE achieve a much reduced correct guess probability compared with RBE. Even with small n values, the correct guess probabilities of DBE and ODBE are very close to the lower bound and ODBE is slightly better than DBE. This analysis illustrates that both DBE and ODBE are less vulnerable to the guessing attack than RBE.

4.2 The Anonymity of Encoded IDs

In this subsection we introduce the degree of anonymity which is a privacy protection metric for encoded IDs [6], [26]. Anonymity is the state of not being identifiable within an anonymous set, and an anonymous set is the set of all possible IDs with similar characteristics as the original ID. For example, if an eavesdropper receives a 4-bit ID, ‘01XX’, the corresponding anonymous set includes {0100, 0101, 0110, 0111}. The degree of anonymity for RFID systems can be defined by the entropy-based metric proposed in [12]. Consider a set φ of all possible IDs (|φ| = 2^l) and a probability p_i of an ID being the original. The entropy of this system H(φ) is defined by:

\[ H(φ) = - \sum_{i \in φ} p_i \log_2(p_i) \]  

When all the bits are not readable, the system has the maximum entropy denoted by \( H_{max} \). As guessing attacks generate probabilities with a uniform distribution, each element in the anonymous set has the same probability, i.e., \( \forall i, p_i = \frac{1}{2^l} \). Ideally, \( l_c = l \). Therefore,

\[ H_{max} = - \sum_{i \in φ} \frac{1}{2^l} \log_2(\frac{1}{2^l}) = \log_2(2^l) = l \]  

The degree of anonymity can be defined as:

\[ \frac{H(φ)}{H_{max}} \]  

Let \( φ' \) be the possible ID set (|φ'| = 2^l_c), when \( l_c \) number of source bits are not readable. Given \( φ' \), the degree of anonymity for a generated encoded ID, denoted as \( d_{φ'} \), is defined by:

\[ d_{φ'} = - \sum_{i \in φ'} \frac{1}{2^{l_c}} \log_2(\frac{1}{2^{l_c}}) \cdot \frac{1}{l} = \frac{l_c}{l} \]  

For example, consider a bit string of ‘XX101X1X0’ received after the encoded ID collided with the mask. Clearly, \( l = 8 \) and \( l_c = 4 \). Accordingly, \( d_{φ'} = 0.5 \).

4.3 Correlation Attacks

To the best of our knowledge, no previous research has discussed correlation attacks in RFID system backward channels. The analytical models of correlation attack for our DBE and ODBE schemes as well as the privacy masking and RBE techniques are presented here.

For the privacy masking protocol, the probability that a source bit does not collide with the mask is 0.5. The number of bits which are identified after the t-th interrogation cycle, denoted as \( R(t) \), is formalized by the following equations.

\[ R(1) = l \cdot \frac{1}{2} \]  
\[ R(2) = R(1) + (l - R(1)) \cdot \frac{1}{2} \]  
\[ R(3) = R(2) + (l - R(2)) \cdot \frac{1}{2} \]  
\[ R(t) = R(t - 1) + (l - R(t - 1)) \cdot \frac{1}{2} \]  
\[ = l \cdot (1 - \frac{1}{2^t}) \]  

For the randomized bit encoding protocol, the fraction \( \frac{1}{2^t} \) in the above equations is replaced by \( \frac{1}{2^r} \) and we can derive the following equation:

\[ R(1) = l \cdot \frac{1}{2^r} \]  
\[ R(t) = R(t - 1) + (l - R(t - 1)) \cdot \frac{1}{2^r} \]  
\[ = l \cdot \{1 - (1 - \frac{1}{2^r})^t\} \]  

For DBE and ODBE, the \((i-1)\)-th bit needs to be identified to recover the i-th bit. Recall the symbol \( pr_i \) defined in Equations 7 and 10 for DBE and ODBE, respectively, which is the probability that the i-th bit is identifiable. Hence,

\[ R(1) = \sum_{k=1}^{l} k \cdot pr_k \]  
and, \( R(t) \) is formalized by:
degree of security. Furthermore, in any encoding scheme, communication efficiency is not compatible with other desirable properties such as anonymity, error correction, etc. [10].

5.2 Expected Time for Tag Singulation

As discussed in Section 3.5, DBE and ODBE can be applied to both tree-walking and Aloha-based singulation protocols. In tree-walking singulation, the expected time for tag singulation is calculated by the number of queries that a reader requests. At first glance, the number of queries increases in proportion to the size of the set of all possible codewords, as the size of a tree becomes larger. However, surprisingly both DBE and ODBE have the same expected time for tag singulation in tree-walking singulation as the privacy masking scheme without encoding, as long as the number of tags in the system is the same.

Theorem 1 In tree-walking singulation, DBE and ODBE have the same expected time for tag singulation as the no encoding scheme, as long as the number of tags in the system is the same.

Proof: We prove the above claim by showing the expected number of queries that a reader requests is independent from the length of pseudo IDs. When a reader sends a query with a bit string, if more than one node have the same prefix in their IDs, collision will occur. When the length of a prefix, denoted by \( l_p \), is one and the number of tags in a system is \( T \), approximately half of \( T \) tags reply to the query. Given a prefix with the length \( l_p \), responses from tags collide with the probability of \( 1 - (1 - \frac{1}{2})^{T-1} \). Similarly, when \( l_p = 2 \), the probability that collision happens is \( 1 - (1 - \frac{1}{2})^{T-1} \). Hence, given a prefix with the length \( l_p \) and \( T \), the probability that responses from tags collide is calculated by \( 1 - (1 - \frac{1}{2^{l_p}})^{T-1} \). This indicates that the probability that responses collide is independent from the pseudo ID length. The number of queries increases in proportion to the number of collisions in responses from tags. Therefore, the number of queries is independent from the length of pseudo IDs. This completes the proof.

In Aloha-based singulation, the expected time to identify all tags in the system is measured by the number of frames. Intuitively, encoding schemes do not affect the expected time to tag singulation, which is shown in the following Theorem.

Theorem 2 In Aloha-based singulation, DBE and ODBE have the same expected time for tag singulation as no encoding scheme, as long as the number of tags in the system is the same.

Proof: We prove the above claim by showing the expected number of frames that a reader sends is independent from the length of pseudo IDs. Let \( s \) (here \( s \geq T \)) be the number of slots in a frame, and the length of pseudo IDs is \( N_{\text{max}} \cdot l \) for DBE and \( n \cdot l \) for ODBE. Given a frame, each tag sends its pseudo ID in a randomly selected slot. The probability that more than one tag chooses the same slot is \( 1 - \frac{1}{N_{\text{max}} \cdot l} \). If collision occurs, collided tags select a different slot in the next frame.
frame. Denoting $s_t$ the number of idle slot at $t$-th cycle, the probability that more than one tag chooses the same slot is:

$$1 - \frac{(T - (s - s_t))!}{(T - (s - s_t))^{s_t}}$$

(32)

Note that $T - (s - s_t)$ is the number of tags that have not being assigned slots. Equation 32 shows the probability that collision occurs is independent from the size of pseudo IDs. The expected number of frames to identify all tags in the system is dominated by frequency of collisions rather than the length of pseudo IDs. This concludes the proof.

Note that DBE and ODDBE enlarge the real tag ID, and, hence, the size of slots in frames needs to be enlarged by $N_{\text{max}}$ times in DBE and $n$ times in ODBE. We consider the increase of the slot size as communication overhead, since it affects the amount of data transmission. This validates our discussion in the previous section, which states that DBE and ODBE increase communication overhead by $N_{\text{max}}$ times in DBE and $n$ times in ODBE.

6 EXPERIMENTAL VALIDATION

To evaluate the performance of the proposed DBE and ODBE schemes, we compared our techniques with no encoding [3] and RBE [18] under the environment with trusted masking device (TMD) deployment. In this section, the simulation configurations, the simulation results and the comparisons between the simulation and analytical results are presented.

6.1 Simulation Configurations

In our simulation, the length of the original ID is set to be 96 bits as defined in EPC Class1 Gen2 [8]. The value of $n$ in RBE and ODBE, as well as $N_{\text{max}}$ in DBE, range from 2 to 10. For the singulation protocol, the adaptive query splitting mechanism [21] is used to identify 100 tags in the RFID system. For a given configuration, 1,000 simulations are conducted. In order to achieve a fair comparison, the value of $n$ for ODBE and RBE corresponds to $N_{\text{max}}$ used for DBE. Consequently, the communication overhead for all protocols is exactly the same. Table 2 lists all of the simulation parameters.

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Simulation parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Number of tags</td>
<td>100</td>
</tr>
<tr>
<td>Length of the original ID</td>
<td>96-bit</td>
</tr>
<tr>
<td>Value of $n$ and $N_{\text{max}}$</td>
<td>2 to 10</td>
</tr>
<tr>
<td>Number of interrogation cycles</td>
<td>1 to 1000</td>
</tr>
<tr>
<td>Number of simulations</td>
<td>1000</td>
</tr>
</tbody>
</table>

6.2 Simulation Results

Figure 7 illustrates the degree of anonymity for generated encoded IDs as a function of the value of $n$. In this figure, each point indicates the average anonymity for each encoded scheme, and the range represents the span of anonymity values obtained by the simulations. As the value of $n$ increases, the degree of anonymity increases for all protocols DBE, ODBE and RBE. Even when the value of $n$ is small, DBE and ODBE achieve very high anonymity compared with RBE. For example, for $n = 2$, the anonymity of DBE and ODBE already reaches 0.99. These results clearly illustrate that our DBE and ODBE schemes achieve a stronger protection than RBE.

Figure 8 displays the time that an attacker needs to crack a tag ID as a function of the value of $n$. In this figure, each point depicts the average required time to crack an ID for each encoded scheme, and the range represents the extent of the required time obtained by the simulations. Attackers accumulate readable bits across interrogation cycles, and, when all bits of an encoded ID are identified, the original ID is disclosed. As we can see in Figure 8, for all protocols except the no encoding scheme (privacy masking), a longer time is required to crack an ID as the value of $n$ increases. ODBE always requires more time than the other protocols. For DBE, when $n$ is less than 7, it performs better than RBE. In reality, it is very unlikely for attackers to be near a tag for more than 1,000 interrogation cycles. Consequently, the results indicate that our DBE and ODBE schemes provide much stronger privacy protection for RFID systems.

Figure 9 shows the communication overhead with respect to the value of $n$. It is clear that for larger values of $n$, a tag has to transmit more bits, and the communication overhead increases proportionally. As discussed in the Dynamic Bit Encoding Scheme subsection of Section 3, theoretically the overhead of DBE and ODBE are the same as RBE and the experimental results validate this assertion. As illustrated in Figures 7 and 9, our DBE and ODBE achieve higher anonymity than RBE by paying the same overhead. Since passive tags have limited computational resources, achieving high anonymity with low overhead is very important. Our simulation results demonstrate
that DBE and ODBE are higher performing privacy protection schemes than RBE.

Figures 10, 11, and 12 demonstrate the degree of anonymity for correlation attacks for three values of \( n \) with respect to the number of interrogation cycles. We assume that each tag generates its encoded ID every interrogation cycle. As can be seen from the three figures, the larger the value of \( n \), the higher a degree of anonymity is achieved. DBE and ODBE always accomplish a higher anonymity than the other two protocols. Also, compared with DBE, ODBE has a slightly higher anonymity. These figures suggest that DBE and ODBE are less vulnerable to correlation attacks than both RBE and the pure privacy masking scheme.

6.3 Comparison between Analytical and Simulation Results

To validate our analytical models it is important to observe a good correspondence between the analytical and simulation results.

Figure 13 illustrates the degree of anonymity with respect to the value of \( n \). In this figure, each point symbolizes the average anonymity for each encoded scheme, and the range represents the span of anonymity values obtained by the simulations. As can be seen from the graphs, the correspondence between the analytical and simulation results for DBE and ODBE is excellent with a marginal difference of only \( 10^{-4} \). This implies that our analytical models provide very accurate estimations in terms of anonymity for both DBE and ODBE.

Figures 14 and 15 present the degree of anonymity for DBE and ODBE against the correlation attack as a function of the number of interrogation cycles. As can be seen from these figures, there are no significant differences between analytical and simulation results.

7 CONCLUSION AND FUTURE WORK

Privacy protection is one of the most important aspects of RFID applications. In this paper, we have proposed two bit encoding schemes for backward channel protection, namely Dynamic Bit Encoding and Optimized Dynamic Bit Encoding. In our design, the codeword length is dynamically changed for each source bit. This increases the level of difficulty for attackers to calculate and identify the original tag IDs. The simulation results show that our DBE and ODBE outperform previous solutions under conditions of original ID guessing.
and correlation attacks. In addition, analytical models are created to estimate the correct guess probability, the anonymity of an encoded ID and the anonymity of a tag. Furthermore, the communication overhead and time complexity of both DBE and ODBE are analyzed. The analytical models are validated through comparisons with simulation results.

While our DBE and ODBE schemes provide much stronger backward channel protection in RFID systems than existing solutions, both of them bring about communication overhead. Specifically the communication overhead increases in proportion to the codeword length. In the future, we plan to develop mechanisms which incur less communication overhead, preferably with the same backward channel protection capability.

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Let $\text{poly}(N_{\text{max}}, l)$ be any polynomial function of the code-word length $N_{\text{max}}$ and the ID length $l$. Since the first source bits of two different IDs could be the same and the first code-word length is always $N_{\text{max}}$, the first codewords of two different IDs could be the same. The probability of two first source bits to be the same is $\frac{1}{2}$, and the probability of first codewords to be the same is $\frac{1}{2^{N_{\text{max}}-1}}$. The rest of $(l-1) \cdot N_{\text{max}}$ bits in a pseudo ID are randomly encoded based on randomly encoded previous codewords. Therefore, the probability that two pseudo IDs collide is $\frac{1}{2} \cdot \frac{1}{2^{N_{\text{max}}-1}} \cdot \frac{1}{2^{l-1}N_{\text{max}}}$, which is smaller than $\frac{1}{\text{poly}(N_{\text{max}}, l)}$ when $N_{\text{max}}$ and $l$ are sufficiently large (which can be easily fulfilled by current RFID standards). Therefore, the chance of a pseudo ID collision is negligible. This completes the proof.

B. Proof of Equation 20

**Proof:** The proof is by induction on $t$. The proposition is $R(t) = l \cdot (1 - \frac{1}{2^t})$.

**Induction base:** When $t = 1$, $R(1) = l(1 - \frac{1}{2}) = l \cdot \frac{1}{2}$. The proposition is true.

**Induction step:** We assume $R(t) = l \cdot (1 - \frac{1}{2^t})$ to prove $R(t + 1) = l \cdot (1 - \frac{1}{2^{t+1}})$.

Let $t = 1$.

Then,

$$R(t + 1) = R(t) + (l - R(t)) \cdot \frac{1}{2}$$

$$= \frac{1}{2} \cdot R(t) + l \cdot \frac{1}{2}$$

$$= \frac{1}{2} \cdot \left(l \cdot \left(1 - \frac{1}{2^t}\right)\right) + l \cdot \frac{1}{2}$$

$$= l \cdot (1 - \frac{1}{2^{t+1}})$$

This concludes the proof.

C. Proof of Equation 23

**Proof:** The proof is by induction on $t$. The proposition is $R(t) = l \cdot \left\{1 - \left(1 - \frac{1}{2^t}\right)^t\right\}$.

**Induction base:** When $t = 1$, $R(1) = l \cdot \left\{1 - \left(1 - \frac{1}{2}\right)ight\} = l \cdot \frac{1}{2}$. The proposition is true.

**Induction step:** We assume $R(t) = l \cdot \left\{1 - \left(1 - \frac{1}{2^t}\right)^t\right\}$ to prove $R(t + 1) = l \cdot \left\{1 - \left(1 - \frac{1}{2^t}\right)^{t+1}\right\}$.

Let $t = 1$.

$$R(t + 1) = R(t) + (l - R(t)) \cdot \frac{1}{2^t}$$

$$= \left(1 - \frac{1}{2^t}\right) \cdot R(t) + l \cdot \frac{1}{2^t}$$

$$= \left(1 - \frac{1}{2^t}\right) \cdot \left\{1 - \left(1 - \frac{1}{2^t}\right)^t\right\} + l \cdot \frac{1}{2^t}$$

$$= l \cdot \left\{1 - \left(1 - \frac{1}{2^t}\right)^{t+1}\right\}$$

This concludes the proof.
D. Proof of Equation 29

Proof: The proof is by induction on \( t \). The proposition is
\[
R(t) = t \cdot \sum_{k=1}^{l} k \cdot pr_k.
\]

Induction base: When \( t = 1 \), \( R(1) = \sum_{k=1}^{l} k \cdot pr_k \). The proposition is true.

Induction step: We assume \( R(t) = t \cdot \sum_{k=1}^{l} k \cdot pr_k \) to prove
\[
R(t + 1) = (t + 1) \cdot \sum_{k=1}^{l} k \cdot pr_k.
\]

\[
R(t + 1) = R(t) + \sum_{k=1}^{l} k \cdot pr_k = t \cdot \sum_{k=1}^{l} k \cdot pr_k + \sum_{k=1}^{l} k \cdot pr_k
\]
\[
= (t + 1) \cdot \sum_{k=1}^{l} k \cdot pr_k.
\]

This concludes the proof.

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