Interference Cancellation-based RFID Tags Identification

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ABSTRACT

In this paper we investigate interference cancellation to faster identify tags in RFID networks. We explore how interference cancellation can be applied to ALOHA and tree-based identification schemes, its limitations, the extent of achievable improvements, and the overhead incurred to obtain effective gains. Analytical and simulation results show that for an ALOHA-based scheme interference cancellation allows us to identify nearly 23% of tags without directly interrogating them. This speeds up tag identification (over 20% faster) while producing little overhead. For a tree-based scheme nearly 50% of the tags are identified by exploiting interference cancellation, resulting in an improvement of the identification rate of over 20%. Finally, we propose an enhancement of the tree-based scheme with interference cancellation that achieves a further identification speed up of 50%.

Categories and Subject Descriptors

C.2 [**Computer-Communication Networks**]: Network Protocols

General Terms

Performance

1. INTRODUCTION

Radio Frequency IDentification (RFID) tags [20] are used to identify objects onto which they are attached. These tags are read by an RFID reader, thereby enabling a range of tasks such as identification, tracking, monitoring, etc. Passive RFID tags use the energy derived from the RFID reader transmissions to transmit data using FSK backscatter modulation [16].

The purpose of an RFID network is often labeling and automation of inventory management in diverse environments. Each RFID tag has a globally unique electronic product code (EPC) or ID. Specifications for RFID, like EPCglobal [1] and ISO/IEC 18000 [7] allow IDs to be up to 256 bits long (including some checksum bits). In a dense deployment of RFID tags, rapid identification of all tags within communication range of the reader is an imperative. This requires all tags to transmit their IDs to the reader, which may lead to tag-tag collisions when replying to the reader queries.

In this paper, we consider the case of a single reader querying a set of passive tags. Several schemes, referred to as anti-collision mechanisms, have been proposed to make tag identification efficient. Two of the prominent categories of these schemes [18] are *ALOHA-based* and *tree-based*. ALOHA-based schemes allocate frames comprised of slots. Each unrecognized tag transmits in a randomly selected slot. Only those tags that transmit alone in a slot are recognized. As long as tags remain to be recognized, more frames are issued. In contrast, tree-based schemes query nodes based on a specific criteria such as prefix of ID or generated random numbers. Tags are recursively split into subgroups until single tag groups are obtained and thereafter identified.

With existing solutions, when collisions occur at a reader due to the concurrent transmission by multiple tags, no tags are recognized and the signal received is of little use. Previous work [11] showed that almost 50% of the identification time is wasted in collisions. In this paper, we propose to use *interference cancellation (IC)* to utilize the signal of collisions to improve the tag identification rate. For example, let tags T_1 and T_2 transmit concurrently and the combined signal received at the reader be Y_{12}. Existing anti-collision schemes require all colliding tags to retransmit later. Let tag T_1 transmit next so that the signal received at the reader is Y_1. If instead of requiring tag T_2 to retransmit as well, the *residual signal* $Y_{12} - Y_1$ is demodulated, T_2 may be recognized depending on the signal-to-noise ratio (SNR) of this residual signal. We refer to tags recognized due to interference cancellation as "inferred" tags in the rest of this work.

In this paper we make the following contributions:

- We apply interference cancellation to two anti-collision mechanisms representative of ALOHA-based and tree-based schemes: Tree Slotted ALOHA (TSA) [3] and Query Tree (QT) [13]. The interference cancellation-based protocols are termed ICTSA and ICQT, respectively. We investigate the performance of ICTSA and ICQT analytically and through simulation showing the gain in identification rate they obtain. Our results show that interference cancellation enhances identification rate by up to 20% for both TSA and QT. We also determine the efficacy of interference cancellation by measuring the fraction of tags inferred and the number of interference cancellations attempted per tag (called

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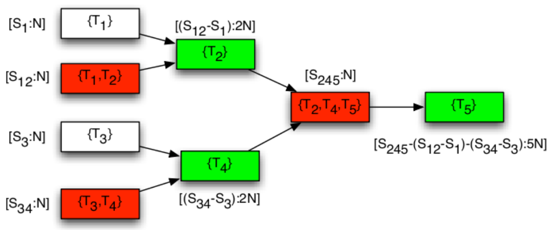


Figure 1: Example of interference cancellation.

overhead). ICTSA infers up to 23% of the tags by just imposing a 0.34 overhead per inferred tag. When applied to QT, interference cancellation infers 50% of the tags while requiring an average overhead of 1.22 per tag.

- We propose an enhancement of ICQT. This enhanced version of the protocol, termed E-ICQT, exploits failures in applying interference cancellation to skip reader queries that would lead to collisions or no replies. E-ICQT increases the identification rate up to 50% with respect to ICQT, and an overall 80% with respect to QT.

The rest of this paper is organized as follows. Section 2 provides background information on interference cancellation for RFID. We then present the details of ICTSA and ICQT and analyze their identification rate performance in Section 3. Simulation results are presented in Section 4. Section 5 introduces and investigates E-ICQT. Section 6 presents related works and Section 7 concludes the paper.

2. BACKGROUND

In this section we provide details of interference cancellation for RFID tags. We use and extend the notation of Zhang et al. [25]. Let T_i denote a tag, its ID, as well as the application level packet that it transmits to an RFID reader. The packet T_i is turned into X_i by the channel coding and modulation layer. After the transmission is successfully received as signal Y_i by the reader it is demodulated back into packet T_i. Let x, y, and t denote a symbol from packets X, Y and T, respectively. The following relation holds:

$$y_i = n + h_i x_i$$

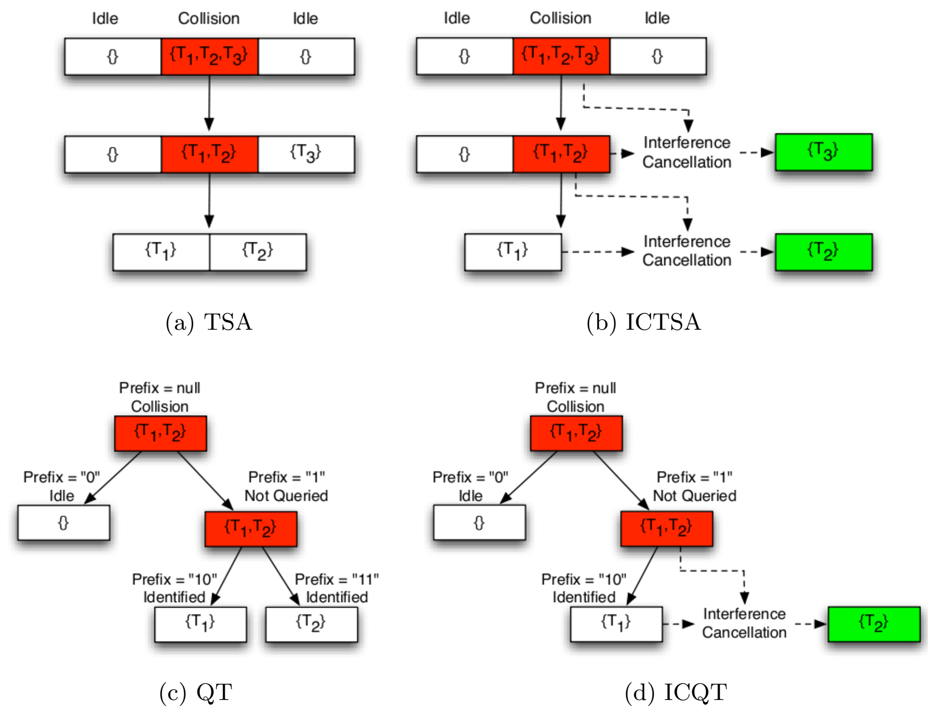
where h_i is the complex path loss coefficient for the channel from tag T_i to the reader and n is the time-dependent noise at the reader (assumed to be complex Gaussian with unit variance [25]). When a set of tags T transmit concurrently, the signal received at the reader is $n + \sum_i h_i x_i$ where $h_i x_i$ is the signal received by reader from tags T_i in the set T. Since tag identification is generally accomplished in a few seconds [11], the tags and the reader can be assumed to be nearly stationary during the identification process. As a result, the noise and the transmission power of a tag at the reader can be assumed to be relatively stable.
According to Fuschini et al. [5], the bit error rate (BER) of the transmission of a tag when received at the reader is given by

$$BER = \frac{1}{2}\text{erfc}\left(\frac{|V_0| \cdot m}{2 \cdot \sqrt{2} \cdot \sigma}\right) \qquad (1)$$

where V_0 is the voltage at the reader, σ is the standard deviation of the Additive White Gaussian Noise (AWGN), and m is the modulation index. As factors like multipath or electromagnetic coupling due to nearby objects become more prominent, m decreases from an ideal value of 0.8 to a low value of 0.2. Let the average power of the noise at the reader (based on clear channel assessment) be NdB. Let the average power of tag T_i transmission at the reader be S_i dB. (Unless stated explicitly, a signal does not contain noise and all power levels are in dB.) Based on Equation (1) the packet error rate (PER) for 56 and 96 bit IDs [10, 11] goes from 1 to 0 over a small range of 4dB. With larger packet sizes, this range of SNR in which PER transitions from 1 to 0 decreases. Due to this sharp transition, we assume that when the SNR $S_i - N$ is greater than or equal to a threshold τ, upon demodulation the checksum of the tag will match and the ID is correctly received. At lower SNRs, whether due to signal degradation or collision, the packet received is erroneous and the checksums of the tag IDs do not match.
Figure 1 shows an example of the interference cancellation approach used here. Each node represents either a successful transmission, a collision, or an inferred signal, and is annotated with the relevant set of tags, the corresponding signal, and noise powers. When the difference of the signals of $\{T_1, T_2\}$ and $\{T_1\}$, referred to as *residual signal*, is demodulated, it may lead to tag T_2 being recognized. The power of this residual signal is $S_{12} - S_1$. However, its noise component is $2N$ since subtracting signals does not cancel noise; instead, noise components are added [24]. As a result, the SNR of the residual signal is $(S_{12} - S_1) - 2N$. An important consequence of the increasing of noise is that the SNR of successively inferred packets using interference cancellation decreases. Since the SNR of the residual signal must be greater than or equal to the threshold τ, this limits the extent of the possible interference cancellation. For example, in Figure 1 the residual signal for tag T_5 has the power $S_{245} - (S_{12} - S_1) - (S_{34} - S_3)$ while its noise component is $5N$. The SNR of this residual signal may not be high enough to be demodulated correctly.
Note that this kind of interference cancellation is based on difference of signals from *different* transmissions. In contrast, capture effect [9] and successive interference cancellation [6] use the difference of signals *derived* from the *same* transmission. To demonstrate the effectiveness of interference cancellation as a stand-alone technique for improving tag identification in this paper we do not consider capture effect or successive interference cancellation.

3. APPLYING INTERFERENCE CANCELLATION

In this section we introduce interference cancellation-based Tree Slotted ALOHA and Query Tree protocols, termed ICTSA and ICQT, respectively. We also analyze their performance in terms of tag identification rate. In order to provide an upper bound on the gain obtainable through interference cancellation, we analyze the considered identification schemes under the assumption that a native or residual signal can be decoded even if the SNR is below the required threshold.



(a) TSA (b) ICTSA

(c) QT (d) ICQT

Figure 2: Application of interference cancellation to TSA and QT protocols.

3.1 ICTSA

Tree Slotted ALOHA (TSA) [3] initially allocates a frame comprised of slots. Each tag randomly picks one slot in the frame. For each slot that results in a collision of tags, TSA assigns another frame, the *child frame*. Only the tags that collide in a slot transmit in this new frame. A frame can have multiple children and these children frames can have subsequent children frames. A child only has a single parent frame (more accurately, a parent slot in the parent frame). As a result, TSA creates a tree of frames to recognize tags. Consider the example in Figure 2(a) where tags T_1, T_2, and T_3 collide in the second slot of a frame. Hence a child frame is allocated to resolve this collision. T_1 and T_2 again collide in this child frame and need a third frame to recognize them. If interference cancellation is applied to this example, the difference between the signal of collision of tags T_1, T_2, and T_3 from the first frame and that of T_1 and T_2 from the second frame can be used to recognize tag T_3 (Figure 2(b)). Similarly, interference cancellation can be used to infer tag T_2 in the third frame. Note that if a new tag is recognized due to interference cancellation using signals of a slot in a parent frame and that of the initial slots of the child frame, the child frame is terminated even if slots remain in the frame. This is because if any other tag in addition to the inferred tag was yet to transmit in the remainder of the child frame, interference cancellation would have failed. Thus, for this example, interference cancellation reduces the number of slots required from 8 to 6 i.e., a gain of 33% in terms of tag identification rate.

More generally, a collision of tags in a slot provides a signal Y. In the child frame allocated to resolve this collision, after every non-idle slot, a cumulative signal Y_c is obtained by combining the signals of all non-idle slots up to this time. After each non-idle slot (except the last slot in a frame), interference cancellation is attempted on the residual signal $Y - Y_c$. If demodulating this residual signal leads to a tag being recognized, the rest of the child frame is truncated since interference cancellation will not be successful if any other tags remain to be discovered. If interference cancellation does not lead to a tag being recognized, it could be due to either multiple remaining tags, zero remaining tags, or low SNR; there is no way to differentiate among these outcomes. Hence in this case the remainder of the frame is not terminated.

TSA Analysis: A critical issue with TSA (and ICTSA) is to optimally set the size of each frame. A constant frame size may lead to either too many idle slots or too many collisions. We first determine how to set the frame size to maximize the rate at which tags are recognized by TSA.

Let the number of tags to transmit in the frame to be allocated be n and the number of slots in the frame be $s(n)$. Since tags independently and uniform randomly select the slot in which to transmit, the probability of k out of n tags transmitting in one of the $s(n)$ slots in a frame is

$$p(s(n), n, k) = \binom{n}{k} \left(\frac{1}{s(n)}\right)^k \left(1 - \frac{1}{s(n)}\right)^{n-k} \quad (2)$$

Interestingly, an idle slot may not be the same size as a non-idle slot. Khandelwal et al. [8] note that when no response is received for a delay corresponding to 10 bits, the reader terminates a slot and indicates the beginning of the next slot. Let β be the ratio of the size of an idle slot to that of a non-idle slot. β depends on several factors - number of bits in the ID, modulation used, delay before terminating an idle slot, etc. Different values of β have been used in prior work [8, 11, 17]. We adopt the values of β used in La Porta et al. [11] - $\beta = 0.03$ for ALOHA-based schemes and 0.13 for tree-based schemes. Since contemporary research has often considered the case of all slots being the same duration i.e., $\beta = 1$, we present results for $\beta = 1$ as well.

Given β, the rate at which tags are recognized by TSA in a frame is

$$R(s(n)) = \frac{p(s(n), n, 1) \cdot s(n)}{s(n) - (1-\beta) \cdot p(s(n), n, 0) \cdot s(n)} \quad (3)$$

where $p(s(n), n, 1) \cdot s(n)$ is the number of tags recognized in the frame and $p(s(n), n, 0) \cdot s(n)$ is the number of idle slots. When $\beta = 1$, $s(n) = n$ leads to maximum tag recognition rate i.e., the number of slots in a frame should be the same as the number of tags that transmit in the frame. When $\beta = 0.03$, $s(n) = 4.4n$ maximizes this rate (as also observed in La Porta et al. [11]). *For brevity, hereon we adopt the notation that $\{A, B\}$ will indicate that the value corresponding to $\beta = 1$ is A and that for $\beta < 1$ is B.* Hence for TSA, $s(n) = \{n, 4.4n\}$ maximizes the tag recognition rate. Note that the frame size is larger for smaller value of β because large frames can be used to decrease collisions, while incurring an insignificant penalty of more idle slots.

Let the number of slots in the tree of frames to recognize n tags be $X(n)$. Let the root frame consist of $s(n)$ slots. For collision of $k \geq 2$ tags, TSA is recursively invoked. Hence the number of slots in a TSA tree of frames is given by the number of slots in the root frame plus the number of slots in children frames of collision slots i.e.,

$$X(n) = \begin{cases} 1 & \text{if } n = 1, \\ s(n) + s(n) \cdot \sum_{k=2}^{n} p(s(n), n, k) \cdot X(k) & \text{if } n > 1. \end{cases} \quad (4)$$

where $s(n)$ is the number of slots in the root frame. $s(n) \cdot p(s(n), n, k)$ is the number of slots that lead to collision of k tags, each of which requires $X(k)$ slots to identify these colliding tags. Note that $X(n)$ is recursively defined.

Similarly, the number of silent slots in this tree of frames is

$$Y(n) = \begin{cases} s(n) - 1 & \text{if } n = 1, \\ p(s(n), n, 0) \cdot s(n) + & \\ s(n) \cdot \sum_{k=2}^{n} p(s(n), n, k) \cdot Y(k) & \text{if } n > 1. \end{cases} \quad (5)$$

where $p(s(n), n, 0) \cdot s(n)$ is the number of idle slots in the root frame. Note that when $n = 1$, the number of idle slots in a frame is $s(n) - 1$.

Hence the rate of recognizing tags in TSA i.e., the ratio of the number of tags to the total identification delay in terms of non-idle slots is

$$R = \frac{n}{X(n) - (1-\beta) \cdot Y(n)} \quad (6)$$

As a result, for TSA, $s(n) = \{n, 4.4n\}$ maximizes the tag recognition rate and results in $R = \{0.43, 0.81\}$.

ICTSA Analysis: Now, lets consider the impact of augmenting TSA with interference cancellation. Let $r(s(n), n, k, j)$ (Equation (7)) be the probability that interference cancellation truncates the current frame with k slots remaining such that j tags transmit in the $(k+1)$-th last slot. The total number of ways in which n tags can transmit in $s(n)$ slots is $s(n)^n$. Out of these, the number of ways in which 1 tag transmits in the last k slots while j tags transmit in the $k+1$-th last slot and the remaining tags transmit in the remaining slots is $\binom{n}{1} \cdot \binom{n-1}{j}$. But 1 tag can transmit in k slots in $\binom{k}{1}$ ways. Moreover, these tag groups can be ordered in 3! ways, and only one is the case we consider. Finally, the $n-1-j$ tags in the first $s(n)-(k+1)$ slots can transmit in $(s(n)-(k+1))^{(n-1-j)}$ ways. This leads us to the expression in Equation (7).

The total number of slots required with interference cancellation is $X'(n)$ (Equation (8)) where $j \in [1, n-1]$ is the number of tags that collide in the $(k+1)-th$ last slot. The expected number of slots in the frame saved due to the frame being truncated is $\sum_{k=1}^{s(n)-1} \sum_{j=1}^{n-1} (r(s(n), n, k, j) \cdot k)$. Note that to enable interference cancellation in the root frame, the signal of all transmitting tags together needs to be available. This can be made available at the cost of an initial frame with only 1 slot. Hence the number of total slots required is $X'(n) + 1$.

The number of silent slots that occur in the tree of frames is $Y'(n)$ (Equation (9)). First, the number of idle slots when a frame is not truncated is $p(s(n), n, 0) \cdot s(n)$. But when a frame is truncated, the number of these idle slots that are saved is $\sum_{k=1}^{s(n)-1} \sum_{j=1}^{n-1} r(s(n), n, k, j) \cdot (k-1)$.

Note that an optimal $s(n)$ for TSA might not be optimal for ICTSA. A small value of $s(n)$ will lead to more collisions while a large value will offer less opportunity for interference cancellation. We arrive at the optimal $s(n)$ for ICTSA by parameter exploration of the expression for its tag identification rate. With interference cancellation, $s(n) = \{0.8n, 3n\}$ leads to maximum rate of recognizing tags $R' = \{0.52, 0.87\}$. Thus interference cancellation improves TSA rate of recognizing tags by $\{21\%, 6\%\}$.

3.2 ICQT

Upon request from a reader, tree-based protocols [4, 14] recursively split tags into two sub-groups until single-tag groups are obtained. Query Tree (QT [13]) protocol queries tags based on a prefix. When a tag ID matches the queried prefix, it replies with the remainder of its ID. Essentially, QT corresponds to exploring the binary tree of the possible prefixes. Another tree-based scheme, Binary Splitting [15], splits tags based on binary random numbers generated by tags. Given a uniform distribution of IDs though, QT behaves like a deterministic version of the Binary Splitting protocol.

A prefix query p may lead to a collision in QT. If so, subsequently, prefix "$p0$" and "$p1$" are scheduled for querying. If "$p0$" is queried and no reply is received, it is apparent that query prefix "$p1$" will lead to a collision. As a result, instead of "$p1$", "$p10$" and "$p11$" are scheduled for querying next. When augmented with this optimization, QT protocols are sometimes referred to as Query Tree Improved (QTI) [13].

Consider the example in Figure 2(c). Let tag T_1 ID be "10..." while that of T_2 be "11...". When the first query for *null* prefix is transmitted, both tags reply. Next the query prefix is "0" and neither of the tags reply to this query. This indicates that querying prefix "1" will lead to a collision. Hence prefix "10" is queried next and only tag T_1 replies and is identified. Next, prefix "11" is queried and only tag T_2 replies and is identified.

Now, consider the case when interference cancellation is applied to this example (Figure 2(d)). Once tag T_1 is recognized, an interference cancellation is attempted between the

$$r(s(n),n,k,j) = \frac{1}{3!}\frac{1}{s(n)^n}\binom{n}{1}\binom{n-1}{j}\binom{k}{1}(s(n)-(k+1))^{(n-1-j)} \tag{7}$$

$$X'(n) = \begin{cases} 1 & \text{if } n = 1, \\ s(n) - \sum_{k=1}^{s(n)-1}\sum_{j=1}^{n-1}(r(s(n),n,k,j)\cdot k) + s(n)\cdot\sum_{k=2}^{n} p(s(n),n,k)\cdot X'(k) & \text{if } n > 1. \end{cases} \tag{8}$$

$$Y'(n) = \begin{cases} p(s(n),n,0)\cdot s(n) & \text{if } n = 1, \\ p(s(n),n,0)\cdot s(n) - \sum_{k=1}^{s(n)-1}\sum_{j=1}^{n-1}(r(s(n),n,k,j)\cdot(k-1)) + s(n)\cdot\sum_{k=2}^{n} p(s(n),n,k)\cdot Y'(k) & \text{if } n > 1. \end{cases} \tag{9}$$

Figure 3: ICTSA analysis

signal received and the signal for the collision corresponding to *closest ancestor node*. This is because the parent of a node may not correspond to an actual query due to the optimization component of QT explained earlier. If the interference cancellation is successful, tag T_2 is recognized. Thus, in this example interference cancellation reduces the number of queries from 4 to 3 i.e., an identification rate gain of 33%.

In general, when a collision is observed for a query prefix "p", prefix "$p0$" is queried next. If a reply is received for this query, an interference cancellation attempt is made using the signals for reply to queries for prefixes "p" and "$p0$". If a tag can be recognized from this residual signal, prefix "$p1$" need not be queried. If a tag is not recognized from the residual signal, because of low SNR of the signal or either zero or multiple tags being involved in the residual signal, prefix "$p1$" is queried.

QT Analysis: Assuming a uniform distribution of IDs among the tags to be identified, the probability of k out of n tags replying to a query when all n tags replied to the prefix query corresponding to the parent node in the query tree is

$$p(n,k) = \binom{n}{k}/2^n \tag{10}$$

Let $X(n)$ denote the number of nodes i.e., queries, in the query tree for QT to identify n tags. Hence

$$X(n) = \begin{cases} 1 & \text{if } n \leq 1, \\ 1 + p(n,0)(X(0) + (X(n)-1)) + \\ \sum_{k=1}^{n} p(n,k)(X(k) + X(n-k)) & \text{if } n > 1. \end{cases} \tag{11}$$

where $X(k)$ and $X(n-k)$ are the number of nodes in the left and right subtree, respectively. Note that for each silent node on the left subtree, the corresponding node on the right subtree is bypassed i.e., not queried, due to the optimization aspect of QT. This leads to the $(X(n)-1)$ component.

Now, the number of silent nodes $Y(n)$ in the query tree is

$$Y(n) = \begin{cases} 1 & \text{if } n = 0, \\ 0 & \text{if } n = 1, \\ \sum_{k=0}^{n} p(n,k)(Y(k) + Y(n-k)) & \text{if } n > 1. \end{cases} \tag{12}$$

Hence, the rate of recognizing tags in QT is $R \simeq \{0.38, 0.44\}$.

ICQT Analysis: When QT is enhanced with interference cancellation, the number of nodes in the query tree does not include the right child of any node that splits into $(n-1)$ tags in the left subtree and only one tag in the right subtree. Hence the number of nodes in the query tree is

$$X'(n) = \begin{cases} 1 & \text{if } n \leq 1, \\ 1 + p(n,0)\cdot(X'(0) + (X'(n)-1)) + \\ p(n,n-1)\cdot X'(n-1) + \\ \sum_{k=1,k\neq n-1}^{n} p(n,k)\cdot(X'(k) + X'(n-k)) & \text{if } n > 1. \end{cases} \tag{13}$$

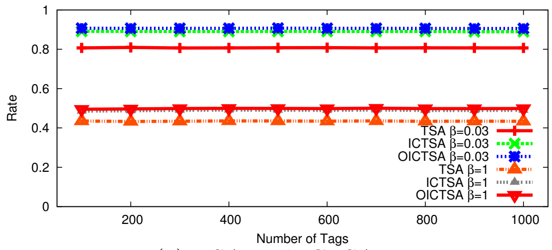
where the element corresponding to $k = n-1$ results in successful interference cancellation and occurs with probability $p(n, n-1)$.

Note that interference cancellation does not reduce silent nodes in the query tree. As a result, the number of silent nodes in the query tree for ICQT is $Y'(n) = Y(n)$. Subsequently, the rate of recognized tags in ICQT is $R' \simeq \{0.46, 0.56\}$. This leads to a gain $\{21\%, 27\%\}$ for tag identification rate.

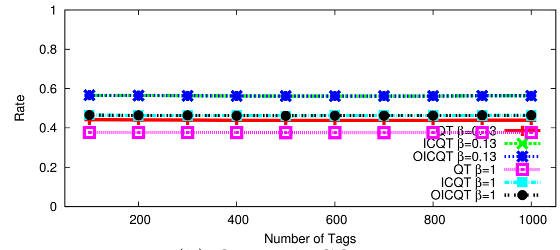
4. RESULTS

We characterize three elements of a tag identification protocol - average number of tags identified per unit time (referred to as *rate*), average fraction of tags identified due to interference cancellation (referred to as *inferred fraction* (IF)), and average number of interference cancellations per tag (referred to as *overhead* (Ovh)). Since the slot duration depends on the modulation used, number of bits in the ID, etc., unit time is considered the same as the duration of a non-idle slot. The IDs of the tags are assumed to be uniformly distributed.

Wu et al. [22] contend that the signal strength of a tag transmission depends mainly on four important factors: The reader transmission power, the distance between tag and reader, relative orientation of reader and tag radios, and the material around a tag. Since tags may be deployed over a large area, the range of signal strengths of tag transmissions may be large. In the results presented here the signal strengths received at the reader are selected uniformly and randomly between 25dB and 50dB. The noise level is set to 5dB. For a signal to be correctly decoded the SNR is required to be greater than $\tau = 18$dB. Since the range of signal strengths and the SNR threshold have an impact on the results of ICTSA and ICQT, we also present results for rate and inferred fraction of variants of ICTSA and ICQT in case of an ideal channel where the SNR does not impact reader reception. There variants are referred to as OICTSA and OICQT in the pictures. They serve the purpose of bounding the gains achievable through interference cancellation.

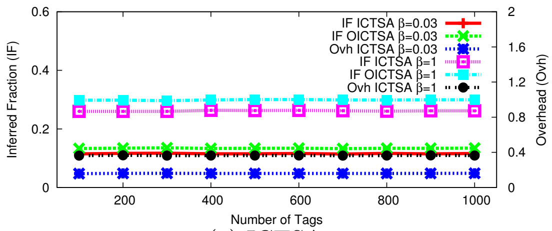


(a) TSA and ICTSA

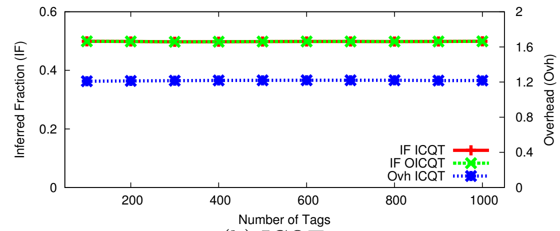


(b) QT and ICQT

Figure 4: Rate.



(a) ICTSA



(b) ICQT

Figure 5: Inferred fraction and overhead.

Clearly, the overhead as defined here metric does not affect OICTSA and OICQT.

All results presented in this section have been obtained through simulations by averaging over 100 different runs.

For the TSA protocol and its interference cancellation based counterparts we suppose to know the number of tags to be identified. Tag cardinality estimation methods [10, 11] allow an accurate measure of the number of tags to recognize in a fraction of the time required to identify them. This allows us to set an initial optimal frame size.

Figure 4(a) shows that the tag identification rate increases from $\{0.43, 0.81\}$ to $\{0.49, 0.89\}$ to $\{0.50, 0.91\}$ for TSA to ICTSA and OICTSA. Hence interference cancellation can bring rate gains of up to $\{16\%, 12\%\}$. Note that the identification rates for $\beta = 0.03$ case are higher than that for the $\beta = 1$ case because the optimal frame size is much larger for $\beta = 0.03$ (Section 3) and the cost of idle slots is negligible.

Figure 4(b) shows the identification rate for QT and its variants. Interference cancellation improves the identification rate from $\{0.38, 0.44\}$ to $\{0.46, 0.56\}$ to $\{0.46, 0.56\}$ for QT to ICQT to OICQT. Though the number of idle and non-idle slots in a query tree is independent of β, a smaller β leads to a reduced identification delay and as a consequence, a higher identification rate. Again, the maximum gain achieved by interference cancellation in terms of identification rate is bounded by $\{23\%, 28\%\}$.

Figure 5(a) shows the inferred fraction and overhead for when interference cancellation is applied to TSA. $\{23\%, 9\%\}$ of the tags are inferred by ICTSA while OICTSA infers $\{27\%, 10\%\}$ of the tags. Again, $\beta = 1$ leads to more interference cancellation primarily due to the optimal frame size being smaller. This is because when $\beta = 0.03$, it is fairly inexpensive to increase the size of a frame and pay the minuscule penalty of excessive idle slots. As a consequence, this leads to an attrition of scope for interference cancellation. The overhead of ICTSA is only $\{0.34, 0.12\}$ interference cancellations per tag.

Figure 5(b) shows the inferred fraction and overhead for QT based schemes. Since QT schemes do not employ the concept of a frame, the inferred fraction and overhead are independent of β. ICQT and OICQT lead to nearly 50% of the tags to be identified due to interference cancellation and the overhead for ICQT is limited to 1.22 interference cancellations per tag.

First, note that ICTSA inferred fraction is less than that for ICQT. This is because only one interference cancellation can be successful per frame for ICTSA while one interference cancellation per internal node in the query tree can be successful for ICQT. Second, the overhead of ICTSA is less than that for ICQT because the number of interference cancellation attempts per frame is nearly the same as the number of non-idle slots in the frame. But the number of non-idle slots is less than the number of tags that transmit in the frame. On the other hand, each internal node in query tree for ICQT results in a collision and presents a candidate for interference cancellation. Hence the overhead of interference cancellation is higher than that for ICTSA.

5. ENHANCED ICQT

In this section we show how for some protocols, such as ICQT, we can use the outcome of interference cancellation to skip some colliding and idle queries, thus further improving the tag identification rate. We term the resulting protocol E-ICQT.

Let us consider a query "x" that causes a collision (see Figure 6). According to ICQT "x" is followed by a query "$x0$" performed by a subset of the tags that generated the collision in the query "x". After this second query, the reader attempts to apply interference cancellation. If the application is successful, it leads to the identification of a tag without querying it. If interference cancellation is not successful, it is because of one of the following two cases. The first case happens when the set of tags responding to "$x0$" is the same that responded to "x". In this case the new query "$x1$" would be idle, and therefore can be skipped. If the set of tags responding to "$x0$" is smaller than the set of tags that

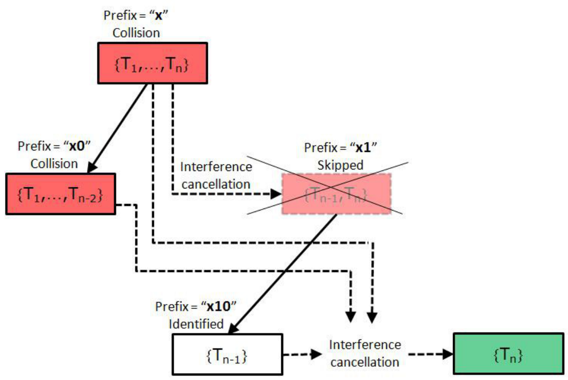


Figure 6: E-ICQT example.

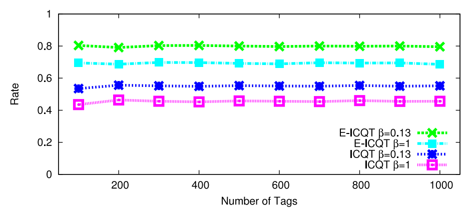


Figure 7: Identification rate for E-ICQT.

responded to "x" (with the difference between the two sets being greater than one tag) the new query "$x1$" would generate a collision. ICQT says that this collision can be used (along with its left son in the tree) to apply interference cancellation at the next tree level. However, we observe that the information provided by such collision can be retrieved by taking the difference between the collisions in "$x1$" father and left brother. As a result, query "$x1$" can be skipped and query "$x10$" can be executed instead. Through this simple reasoning E-ICQT allows us to halve the number of colliding queries, and to reduce the number of idle queries.

Figure 7 shows that the tag identification rate increases from $\{0.46, 0.56\}$ for ICQT to $\{0.69, 0.80\}$ for E-ICQT. Therefore, the improvement over ICQT is up to $\{50\%, 42\%\}$ and, even more remarkably, the improvement over QT is $\{81\%, 81\%\}$. We note that the inferred fraction for E-ICQT is the same as that of ICQT (i.e., 50%). In other words, E-ICQT does not impact on the interference cancellation process. It only smartly exploits known information for reducing time consuming colliding and idle queries without imposing extra overhead, which remain the same of ICQT (i.e., 1.22).

As a matter of fact, interference cancellation can be unsuccessful also because of low SNR (Section 2). However, in order to evaluate the effectiveness of the E-ICQT protocol, here we have considered scenarios with an ideal channel. Also the tag that is eventually not recognized through interference cancellation is queried at the next level. Future work will study the impact of physical layer issues on the E-ICQT protocol performance.

6. RELATED WORK

The application of interference cancellation to identify RFID tags has been proposed previously. A preliminary attempt in presented in [24], that provides an early glimpse into how to apply interference cancellation to a tree-based anti-collision protocol.

A deeper study is presented in [23], where physical layer network coding is applied to a basic Framed Slotted Aloha (FSA) protocol. FSA issues consecutive frames to which all unrecognized tags participate, picking a random slot. The idea in [23] is to apply interference cancellation between a collision slot and one or more single slots. Specifically, they remove from the mixed signal (e.g., $Y_1Y_2 \dots Y_k$) of a collision of k tags, the signals of $k-1$ tag IDs (e.g., $Y_1Y_2 \dots Y_k - (Y_1 + Y_2 + \dots + Y_{k-1})$), received in different single slots. In our work, we apply interference cancellation also when the signal to be subtracted is generated by a collision of multiple tags. The application is successful every time the second group of tags is the same as the first group except for one tag (e.g, $Y_1Y_2 \dots Y_{k-1}$). Another difference with [23] is that our interference cancellation approach is much more lightweight. Applying interference cancellation to FSA requires to *guess* all but one of the tags that collide in a slot to identify a new tag. In other words, whenever a new tag is identified, it may be useful to solve a previous collision. However, the reader does not know in which of the previous collision slots this tag has transmitted. It also does not know with which and with how many other tags the new tag has collided. Therefore, the reader has to attempt an interference cancellation among every collision that happened in earlier frames and every subset of recognized tags, which incur a significant computational overhead.

Our investigation is more general, targeting both ALOHA-based and tree-based identification protocols. The schemes we consider, TSA and QT, provide higher identification rate than FSA. Furthermore, instead of guessing à la FSA, in both our ICTSA and ICQT we use a *parental* relationship between tag collisions and identifications, making the application of interference cancellation immediate, and curtailing the computational overhead significantly. The need of guessing is bypassed by subtracting the signal of a collision or identification directly from the signal of the slot or of the query at the parent level (Section 3).

We finally mention that interference cancellation is not the only technique that can be used for improved identification rate. Other methods, such as capture effect [9] and successive interference cancellation (SIC) [6] can be exploited. Lai et al. [12] observe a pitfall in the application of capture effect to a tree-based protocol. In these protocols, once a tag is recognized based on its reply to a query, the corresponding node in the query tree is marked as a leaf and its descendants are not explored. By using capture effect, tags can be recognized in spite of collisions with other tags. As a consequence, such colliding tags are never detected. Lai et al. [12] propose an efficient method to address this issue.

Tseng et al. [19] partition tags into groups based on the signal strength of tag transmissions. For instance, tags surrounding a reader are broken into four groups. Tags in the first and third group form a partition and the remaining groups form the other partition. To recognize tags belonging to any partition, DFSA is used. By making tags with disparate signal strengths part of the same group, SIC [6] and multi-user detection [21] can be used to recognize tags. The authors report a 5% increment in the tag identification rate. Bhanage et al. [2] use SIC to reduce error rate during tag recognition.

7. CONCLUSIONS

RFID anti-collision schemes do not take advantage of the signal received when tag-tag collisions occur. In this paper we propose to use interference cancellation to use these collision signals to expedite the tag identification process. Our results show that interference cancellation can infer 23% and 50% of the tags when applied to the previously proposed schemed TSA and QT, respectively. In addition, the tag identification rate induced by interference cancellation applied to TSA and QT improves by 20%. Our investigation and results lead us to propose a simple enhancement to ICQT that further improves the identification rate for this tree-based protocol.

8. ACKNOWLEDGEMENTS

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