Collision-resistant Communication Model for State-free Networked Tags

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***Abstract*—Traditional radio frequency identification (RFID) technologies allow tags to communicate with a reader but not among themselves. By enabling peer-to-peer communications among nearby tags, the emerging networked tags make a fundamental enhancement to today's RFID systems. This new capability supports a series of system-level functions in previously infeasible scenarios where the readers cannot cover all tags due to cost or physical limitations. This paper makes the first attempt to design a new communication model that is specifically tailored to efficient implementation of system-level functions in networked tag systems, in terms of energy cost and execution time. Instead of exploiting complex mechanisms for collision detection and resolution, we propose a collision-resistant communication model (CCM) that embraces the collision in tag communications and utilizes it to merge the data from different sources in a benign way. Two fundamental applications: RFID estimation and missing-tag detection, are presented to illustrate how CCM assists efficient system-level operations in networked tag systems. Simulation results show that the system-level applications through CCM are able to reduce the energy cost and execution time by one order of magnitude, compared with the ID-collection based solution.**

I. Introduction

RFID (radio frequency identification) tags are becoming ubiquitously available. Practical RFID systems exist for asset management, automatic payment, access control, fast check-out, theft prevention, etc. An RFID system typically consists of three components: tags, readers, and application software. In today's prevalent application model, tags are treated individually as ID carriers embedded in library books, passports, driver licenses, car plates, medical products or other objects, allowing an RFID reader to quickly identify or access the properties of each individual object.

In recent years, new research has made a paradigm shift from this individual view of tag identification to a collective view of system-level functions [1], which gives rise to an array of new applications and interesting research problems. For example, consider a major distribution center of a large retailer which applies tags to all its products. These tags, which are pervasively deployed in the center, should not be treated just as ID carriers for individual objects. Collectively, they constitute a new wireless platform, which can be exploited for center-wide applications. Along this line of research, much work on system-level functions has been carried out to design efficient protocols for estimating the number of tags in a large RFID system [2]–[7], detecting the missing tags [8]–[11], identifying unknown tags [12], [13], searching wanted tags [14], [15].

Networked Tags: Traditionally, tags can only communicate with readers but not between themselves. An emerging research branch of *networked tags* proposes a fundamental change: peer-to-peer communications are enabled amongst the tags [16]–[22]. The new capability of forming a network provides great flexibility in various applications. Consider a large warehouse (a retail store, a book store, or a library), where a large number of readers must be deployed to provide a complete coverage, which can be very costly. More importantly, communications between readers and tags may be hindered by unforseen, dynamically occurring conditions such as obstacles moving in or tagged objects piling up that sometimes prevent signals from penetrating into every corner of the deployment, causing a reader to fail in reaching some of the tags. This problem will be solved if the tags can relay transmissions toward the otherwise-inaccessible reader.

Networked tags are in their nascent stage of development [19]–[22]. M. Gorlatova et al. [19] design and prototype the first networked tag, with its network model similar to the traditional sensor network and its communication model being CSMA. Future networked tags are not limited to such models and may be powered by internal batteries as many of today's active tags do. To guide the future development of network tags, we believe there needs more theoretical exploration on new network and communication models that consider the limitations of RFID tags and also take advantage of their unique features. A state-free network model was proposed by [16], which captures a key difference between a tag network and a traditional sensor network.

State-free Network Model: There can be two types of networked tags. The *stateful* networked tags maintain state information such as their current neighbors and correct routing tables. These tags are similar to the nodes in a typical sensor network. They have to frequently exchange messages (e.g., beacons for detecting neighbor changes and control packets for routing) to keep state information up-to-date, which costs energy. The *state-free* tags do not maintain any network state prior to operation, which makes them different from traditional networks, including sensor networks — virtually all literature on data-collecting sensor networks assumes the stateful model, where the sensor nodes maintain information about who are

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their neighbors and/or how to route data in the network.

Following [16], this paper considers state-free networked tags not only because there is little prior work, but also because they are more energy-efficient and make more sense for tags. First, establishing neighborship and then building routing tables across the network are expensive and may incur *much more overhead than the simple tag operations* that they are supposed to support. Second, maintaining the neighbor relationship and updating the routing tables (as tags may move between operations) require *frequent* network-wide communications, a cost not worthwhile for *infrequent* operations by tags that sleep most of the time to save energy.

Networked Tags vs. Wireless Sensors: One may concern what the difference is between the networked tags and the wireless sensors. In distributed WSN, each sensor node does a peer-to-peer communication with each other; the peers are almost equally privileged. In networked tag system, however, the communication is highly asymmetric: the reader is more powerful than tags and can transmit its messages to all tags in the field of view via only one-hop transmission. In contrast, the networked tags just communicate with their nearby neighbors due to the limited on-chip resources. This makes multi-hop tag-to-tag relay needed, for the data from outer-tier tags being forwarded and converging towards the reader. Hence, we stress that our focus is on networked tags, with highly asymmetric communication link, to set apart from wireless sensors.

Collision-resistant Communication Model: The goal of this paper is to design a new communication model that is tailored to efficient implementation of system-level functions for state-free networked tags. Our observation is that, unlike traditional wireless systems (such as WiFi networks and sensor networks), the amount of information to be delivered from tags to a reader is very small, often just one bit per tag. It is not worthwhile to implement complex mechanisms for collision detection and resolution, which carry high energy overhead in multi-hop networks, where collision happens hop by hop.

Unlike the prior work that relies on CSMA for explicit collision detection and resolution [16], [19], we propose a collision-resistant communication model (CCM), which embraces collision in tag communications and utilizes it to merge the data from different sources in a benign way. Our model is fundamentally different from traditional collision-resistant techniques such as serial interference cancelation [23], physical-layer network coding [24], and analog network coding [25], which require significant signal processing, memory and computing capabilities that extract individual data items from the mixed physical-layer signals. To meet the low hardware requirement of tags, our model is much less demanding: It does not require tags to perform collision detection and resolution. It does not require tags to record signal waveforms and separate aggregate symbols into individual ones as in [24], [25]. It only requires a tag to be able to tell whether the channel is busy or idle in each time slot, which is energy-efficient.

We show that such a simple primitive can be used to design a communication model that fits well with the functions in RFID systems as we extend them to networked tags. This paper selects two important functions, RFID estimation and missing-tag detection, as examples to demonstrate how to apply our new model to implement system-level functions efficiently, without the need to explicitly detect or resolve collisions when multiple tags transmit together. We use simulations to show that the performance of using the proposed model to implement RFID estimation and missing-tag detection is far better than the ID collection approach (the only approach known to work for networked-tag systems), cutting the energy overhead and the execution time by an order of magnitude.

II. System Model

We consider multiple readers and a large number of objects, each of which is attached with a tag, carrying a battery for power. We will use tag, node and networked tag interchangeably in the sequel. Each tag has a unique ID that identifies the object it is attached to. We consider state-free tags, which do not spend energy in maintaining any state information prior to operation. A networked tag system is different from a traditional RFID system with a fundamental change: tags near each other can directly communicate. This capability allows a multihop network to be formed amongst the tags. Networked tags must be active tags that communicate without wireless energy supply from a reader. They are expected to carry sufficient internal energy for long-term operations. Hence, a new communication model for energy-efficient transmissions is necessary in networked tag systems.

We say there is a link from tag t' to tag t if t can sense transmissions by t'. Regardless of distance, multipath effect or interference model, as long as t can sense transmission by t', the latter is a neighbor of the former. A tag's neighborhood consists of all tags from which it senses transmissions. Readers and tags in the system form a connected network. In other words, there exists at least one path from any tag to one of the readers such that the tag can communicate by transmitting information along that path. Tags that cannot reach any reader are not considered to be in the system.

Since a wideband RF switch alternately connects the transmitter and receiver to the antenna port of a tag, only half duplex communication is allowed [26]. To conserve energy, networked tags are likely configured to sleep and wake up periodically for operations. After wake-up, a tag will listen for a request broadcast from the reader into the network, which either puts the tag back to sleep or asks the tag to participate in an operation such as cardinality estimation. The broadcast request will also serve the purpose of loosely re-synchronizing the tag clock. The reader will time its next request a little later than the timeout period set by the tags to compensate for the clock drift and the clock difference at the tags due to broadcast delay. The exact sleep time of the tags and the inter-request interval of the reader should be set empirically based on application needs and physical parameters of the tags. We assume that the tags are stationary during operation, but they can be moved around between operations. In addition, for ease of presentation, our model is presented for a single reader, but it can be easily extended to the multi-reader case when the collision-free transmission schedule among the readers is established. This will be discussed later in Section III-G.

III. Collision-resistant Communication Model

A. Asymmetric Communication Links

The communication between the RFID reader and the networked tag is a round trip, including the *uplink* from the reader to the tag, and the *downlink* from the tag to the reader. For the uplink, since the reader is considered as an infrastructure with 'unlimite' energy source, it can raise its power and broadcast its request to all tags in the field of view through one-hop transmission. All tags under the reader's (one-hop) coverage can decode its request successfully. For the downlink, due to the limited on-chip resources, the tag's communication range is much lower than the reader's. By the multi-hop tag-to-tag relay together with the one-hop tag-to-reader transmission, the data from outer-tier tags can be forwarded and converge towards the reader.

B. Information Model

We adopt a general information model that is very useful and versatile in supporting system-level functions such as estimating the number of tags [2]–[7], [27], detecting the missing tags [8]–[11], and searching wanted tags [14], [15]. In this model, the reader collects information from tags in the form of a bitmap. Each tag chooses one or multiple bits and sets those bits to 1. The bitmap can be implemented by a time frame where each slot corresponds to a bit. The reader initiates the time frame, and each tag makes a transmission in its chosen slot (or slots). The reader monitors the channel status, and converts each busy (or idle) slot to a bit 1 (or 0). Applications are designed based on the bitmap received by the reader. For example, if each tag chooses a random slot in the time frame, we can estimate the number of tags in the system based on the number of zeros in the bitmap [5], or we can detect missing tags if a time slot that is supposed to be busy turns out to be idle [8]. If each tag chooses multiple random slots in the time frame, we can perform tag search based on the bitmap [14], [15]. All prior work assumes tags can directly communicate with the reader, which makes the problem of collecting the bitmap simple. This assumption does not hold any more with networked tags.

C. Rounds, Frames and Slots

Suppose the reader wants to collect a bitmap from networked tags, each of which sets one or multiple bits in the bitmap. In our collision-resistant model, communications between the reader and tags are performed in rounds. In each round, the reader broadcasts a request, which is followed by a time frame F, where the reader listens to its neighboring tags' transmissions. Also importantly, each tag in the system will listen to its neighbors as well in the slots where it does not transmit. Hence, after the first round, the reader knows the bits set by the neighboring tags. Moreover, these tags collectively know the bits set by their neighbors. In the next round, they will relay those bits to the reader. This process will repeat round by round.

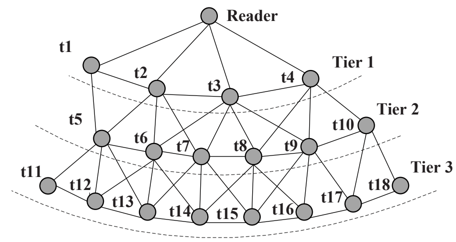

Fig. 1: An illustration of a three-tier network.

One may concern that a tag cannot hear its neighbors in a time slot when it is on transmission. This is true due to the half duplex communication manner in networked tag systems. However, it will not cause any problems: the 'busy' information has been sent out by this tag already; there is no need to re-transmit in this slot again (even though its neighbors picked this slot), as one or multiple replies by tags will produce the same bit '1' in the final bitmap. Hence, once a transmission has been carried out, the tag will go to sleep for saving energy in the same slot of the following rounds. We define the tier-k tags as those whose shortest paths to the reader are k hops long. After the first round, the bits set by tier-k tags are learned by their tier-$(k-1)$ neighbors. After the second round, these bits are relayed from tier-$(k-1)$ tags to tier-$(k-2)$ tags ... After each round, they are relayed one hop closer to the reader. After the kth round, they will be received by the reader. With each round, the reader receives a bitmap with some bits set to 1 (which are originated from a certain tier). The final bitmap is the union of the bitmaps from all rounds.

Fig. 1 illustrates a 3-tier network. Tags t_{1-4} form tier 1 as they can communicate with the reader directly. Tags t_{5-10} are located at tier 2 since their data reach the reader through at least two hops. Similarly, the left tags form tier 3. With above communication model, the tag information is delivered tier by tier, from outer tags converging towards the reader. Each tag will merge the data received in the previous round from its upstream neighbors[1], and transmit the merged data in the current frame to its downstream neighbors. Note that the optimal frame size f is determined by the existing protocol design in the traditional RFID system. We just need to broadcast f only once in the first round. In the following rounds, all tags use the same parameter to build the frame and return the bitmap information to the reader.

D. Indicator Vector

In CCM, since each tag only listens to its neighbors in the slots where it does not transmit, it will not participate in the information relay once a transmission is made in a slot. This control scheme helps avoid duplicate deliveries and infinite loops, and allows messages to eventually expire from the system. However, there is still room for further improvement.

[1]From a tier-k tag's point of view, its tier-$(k+1)$ neighbors are called upstream tags and its tier-$(k-1)$ neighbors are called downstream tags, using the reader as the reference point for the sink of data.

Consider tier-1 tags. Their information not only reaches the reader in the first round, but also floods to their neighbor tags (tier-2 tags if the tag-to-tag link is symmetric). In other words, the wave of inner tags' information will fan out tier by tier towards the outermost tags if no extra action is taken.

To address this problem, the reader is supposed to refrain this like-a-rolling-snowball information flooding. For this purpose, the reader adopts an indicator vector to tell tags which slots are busy and which are not at the end of each round. With such information, if a slot is busy, all tags can leave it alone as repetitive replies by tags in this slot still produce a busy slot. By this means, many duplicate deliveries are avoided, saving the energy overhead. More specifically, the indicator vector V consists of f-bits, each of which corresponds to a slot in the frame F and is set to 0 in the initial. At the end of each round, the reader checks each slot in the frame F. If the ith slot $F[i]$ is proven to be busy, the ith bit of V is set to 1, i.e., $V[i] = 1$. After that, the reader broadcasts this vector to all tags. If the vector is too long, the reader can split it into small segments and transmit each of them in a time slot. Upon receiving this vector, each tag will not listen to its neighbors nor make any transmissions (i.e., goes to sleep) in the ith slot of the following rounds if $V[i] = 1$ holds.

With this rule, the tier-k tags' information must not be relayed again after the execution of the kth round. The reason is that the tags' information converges to the reader in a tier-by-tier manner and one-tier propagation of information takes the delay of one round. After running k rounds, tier-k tags' bitmap information must reach the reader. By broadcasting the indicator vectors, the reader is able to tell all tags which slots picked by tier-j tags ($j \leq k$) are busy (or idle) and the tags will go to sleep in these slots. Hence, the use of indicator vectors avoids most duplicate deliveries, thereby improving the time efficiency as well as saving the energy cost.

E. Number of Rounds

So far we have discussed most details of CCM but not given the answer to the crucial associated question of when the reader terminates the communication, i.e., how many rounds are required to completely collect all tags' information. As previously mentioned, the tier-k tags' information must be forwarded to the reader after the execution of k rounds. Hence, for a K-tier networked tag system, K rounds are necessary. However, K is unknown by the reader as the state-free tags do not maintain any network state (e.g., their current neighbors and correct routing tables) and none of routes are built prior to operation. Actually, each tag even does not know in which tier itself resides.

To address this problem, the reader needs to carry out a short checking frame $\mathcal{C}$ to examine whether or not there are still on-the-way data that have not been relayed to the reader yet. Initially, each tag gives a response in the first slot $\mathcal{C}[1]$ of the checking frame if a transmission is needed by the tag in the next round. Otherwise, it listens to its neighbors. Once a message from its neighbors is detected in the ith slot $\mathcal{C}[i]$, the tag gives a response in the next slot $\mathcal{C}[i+1]$. From the reader's perspective, if a slot is busy (tier-1 tags transmit something), it must be true that some data has not been collected by the reader yet. Hence, the reader terminates the checking frame and advances to the next round. If the reader has not received anything after going through the entire checking frame, the reader has no reason to doubt that all tags' information has been received and it stops the communication. We refer to the communication process for completely collecting the bitmap from all tags as a *session*. Clearly, a session may consist of multiple rounds of communications. Note that the length L_c of checking frame is empirically set to $2 \times (1 + \lceil \frac{R-r'}{r} \rceil)$, where $(1 + \lceil \frac{R-r'}{r} \rceil)$ is an estimate of the number of tiers, R, r', and r are the communication ranges of reader-to-tag, tag-to-reader, and tag-to-tag, respectively.

F. Putting Things Together

Now we put all the pieces together and sketch a session of the collision-resistant communication model (CCM) as follows. As shown in Alg. 1, Line 2 gives an upper bound of the number of rounds. Lines 3-10 detail how to broadcast the request by the reader and how to relay the information by the tags. Lines 11-12 are to refrain the information flooding with the indicator vector V. Line 13 updates the information bitmap

Algorithm 1 A Session of CCM

Input: frame size f; communication ranges R, r', r
Output: f-bit information bitmap B

1: All bits of B are set to 0;
2: $L_c = 2 \times (1 + \lceil \frac{R-r'}{r} \rceil)$;
3: **for** i = 1 to L_c **do**
4: Reader broadcasts a request to launch the ith round
5: Tag listens to its neighbors where it does not transmit
6: **if** i == 1 **then**
7: Each tag picks a slot and gives a reply in that slot
8: **else**
9: Each tag transmits the bitmap learned from its neighbors in the previous round
10: **end if**
11: Reader creates and broadcasts the indicator vector V
12: Tags go to sleep in the ith slot if $V[i] == 1$
13: B = $(B \mid V)$
14: Checking frame $\mathcal{C}$ is carried out
15: Tag gives a one-bit response in $\mathcal{C}[1]$ if a transmission is needed in the next round
16: **for** j = 2 to L_c **do**
17: **if** Reader receives something **then**
18: Go to Line 3
19: **end if**
20: **if** Tag receives something in the slot $\mathcal{C}[j-1]$ **then**
21: Tag gives a one-bit response in the slot $\mathcal{C}[j]$
22: **end if**
23: **end for**
24: break
25: **end for**
26: Return B

B via bitwise-or operation with V. Lines 14-24 determine when the reader terminates the communication. If there are still on-the-way data, the reader goes to the next round (Line 18). Otherwise, the reader returns B and terminates the session of communication (Line 26). According to B, we are able to achieve system-level functions, such as cardinality estimation and missing-tag detection.

G. Multiple Readers

Alg. 1 details CCM in the case of a single reader. It can be easily extended to this case of multiple readers. Assume that there are M readers. These readers can execute in parallel if no reader-to-reader collision happens or be scheduled in a round-robin way otherwise. After that, each reader individually collects a bitmap according to Alg. 1 in its own time window. The final bitmap B of one-session communication is the combine of all bitmaps via bitwise OR:

$$B = B_1|B_2|, ..., |B_i|, ..., |B_M, \tag{1}$$

where '$|$' is bitwise-or operation and B_i is the bitmap collected by the ith reader.

IV. RFID Estimation in Networked Tag System

A. Traditional RFID Estimation

Consider the problem of RFID estimation, which is to provide an estimate $\hat{n}$ for the number n of tags in an RFID system such that

$$Prob\{\hat{n}(1-\beta) \leq n \leq \hat{n}(1+\beta)\} \geq \alpha, \tag{2}$$

where β specifies a relative error. Suppose $\beta = 5\%$ and $\alpha = 95\%$, the above accuracy requirement means that the estimation should be bounded by $\pm 5\%$ error with 95% probability. There is a rich set of solutions in the literature [2]–[7]. However, none of them can be directly applied to networked tag systems because their design is based on the traditional model where tags can only communication with the reader but not amongst themselves. Below we review one of the classical solutions for RFID estimation.

Since the seminal work by Kodialam and Nandagopal [5], many estimators had been proposed, claiming better performance. However, Chen et al. [28] found that their superior performance was not due to the estimators themselves but because of a two-phase design with a preceding rough-estimation phase to set the right parameters for the following phase of accurate estimation. Adding a rough-estimation phase, the methods in [5] still perform better.

We choose an enhanced variant of the zero-based estimator in [5]. The variant is called the generalized maximum likelihood estimator (GMLE) [28]. Still in the context of a traditional RFID system, we adapt the estimator for framed communication between a reader and tags: A reader transmits a series of requests (f, p) to tags in its coverage. Every request is followed by a time frame consisting of f slots, each carrying one bit information. With a sampling probability p, each tag will participate in the frame by pseudo-randomly selecting a slot in the frame to transmit.

The reader monitors each time frame and turns the status of the slots into a *status bitmap* of length f, where each busy slot corresponds to a bit '1' and each idle slot a bit '0'. After each time frame, the reader applies the maximum likelihood method on all bitmaps obtained so far to give an estimate $\hat{n}$ on the number of tags in the system. It then adjusts the sampling probability for the next request to be $p = \frac{1.59f}{\hat{n}}$. Many time frames will be needed in order to reduce the variance of the estimation and achieve the pre-specified accuracy [28].

B. Applying GMLE in Networked Tag Systems through CCM

We show that the collision-resistant communication model can enable the above GMLE estimator for RFID estimation in networked tag systems. Each round here corresponds to a time frame in the traditional RFID system. From the reader's point of view, it sends out a request and receives back a status bitmap, based on which an estimation can be made. We want to configure the data transmitted by tags in the collision-resistant communication model (CCM) such that the reader can produce exactly the same status bitmap as what would be produced in a traditional RFID system where all tags were in the direct neighborhood of the reader.

The reader still transmits a request (f, p) through CCM, where f is the number of slots in each frame and p is the sampling probability that will be used by the tags in a similar way as described previously. After receiving the request, a tag will decide with probability p whether to participate in the status bitmap. If the answer is positive, it pseudo-randomly selects a slot in the frame to transmit. Essentially the tag gives a response in a single slot. In the subsequent rounds (frames), the tag will retransmit the bitmap received from the preceding frame. The reader will receive a series of bitmaps in the different frames from tier-1 tags. It combines all these bitmaps through bitwise OR to produce the final status bitmap.

Theorem 1. *The status bitmap received by the reader under CCM in a networked tag system is identical to that in a traditional RFID system with the same set of tags.*

Proof. Turn a status bitmap in a traditional RFID system into a frame, where a bit '0' corresponds to an idle slot and a bit '1' a busy slot. With identical implementation of sampling and slot selection, each tag will make the same decision on whether to participate in a frame and which slot to choose for transmission, no matter whether the tag is in a traditional RFID system or in a networked tag system. Hence, for an arbitrary idle slot in the traditional RFID system, it will also be true that no tag picks this slot in the networked tag system. Since no tag transmits in this slot, the slot will always stay idle during the tag-to-tag and tag-to-reader transmissions. Once a frame is carried out, the reader decodes this slot as bit '0' for sure. For a series of frames, the bitwise OR of '0's still outputs '0'.

On the other hand, a busy slot in the traditional RFID system means one or more tags in the networked tag system pick this slot. Hence, at least one tag t transmits in the slot. Once receiving t's data, t's downstream tags will decode the slot to '1', and later retransmit in this slot of the next frame.

The process repeats tier by tier until the information reaches the reader, which can correctly decode bit '1' from the busy slot. Performing bitwise OR over many frames received by the reader, as long as there is a single '1' in the bit position, the result will be '1'.

In summary of the above analysis, the status bitmap received by the reader under CCM in a networked tag system must be identical to the status bitmap in a traditional RFID system with the same set of tags. □

C. Execution Time & Energy Overhead

We omit the discussions on the settings of the frame size and the number of status bitmaps needed for meeting the predefined accuracy requirement as they have been analyzed in [28]. We focus on the performance analysis of GMLE in a networked tag system under CCM, in terms of execution time and energy overhead. Let K be the number of tiers in the networked tag system.

1) Time Efficiency: The communication terminates only when the reader receives all bitmaps from each tier. As aforementioned, tier-k tags information must reach at the reader after k-round execution. Hence, for a K-tier networked tag system, K rounds are needed. Consider an arbitrary round. Its major communication delay consists of carrying out the f-slotted frame, broadcasting the indicator vector, and executing the checking frame. Therefore, we have the execution time:

$$T = K(f \times t_s + \lceil \frac{f}{96} \rceil \times t_{id} + L_c \times t_s), \tag{3}$$

where f is the frame size, t_s is the length of the slot that transmits one bit by the tag, and t_{id} is the length of the slot that transmits a 96-bit tag ID by the reader.

2) Energy Overhead: In this section, we analyze a tag's energy overhead in a networked tag system, in terms of the number of slots that the tag takes to receive & transmit something. In the communication model, besides giving a one-bit response in its picked slot, the tag also needs to relay the data from other nodes. Since these delivers rely on the specific network topology when the networked tag system is built, directly deriving the communication overhead irrespective of the network topology is impractical. To make the analysis tractable, we assume that tags are evenly distributed in a zone with density ρ; the transmission ranges of reader-to-tag, tag-to-reader, and tag-to-tag are R, r', and r, respectively, where $R > r'$ and $R > r$. Clearly, the tags whose replies are reachable to the reader via one-hop transmission form tier 1 (the distance to the reader is no greater than r'); tags whose distances to the reader are greater than $r'+(k-2)r$ but smaller than $r' + (k-1)r$ form tier k, $k \geq 2$, in the network.

Fig. 2(a) depicts a network of three tiers. Consider the K-tier network where a tag t is located at tier k. We first derive the number of slots monitored by the tag. In the ith round, when carrying out the frame, the tag needs to monitor the empty slots in the frame. Let Γ_i be the tag set that is reachable to the tag t through at most i-hop transmissions and Γ'_i be the tag set that is reachable to the reader through at most i-hop transmissions. Hence, at the beginning of the ith round, the slots picked by Γ_{i-1} and Γ'_{i-1} will not be taken into account by the tag since these busy slots have been either relayed by the tag t or silenced by the indicator vector broadcast by the reader. Let $\chi(n')$ be the number of different slots picked by n' tags. We have

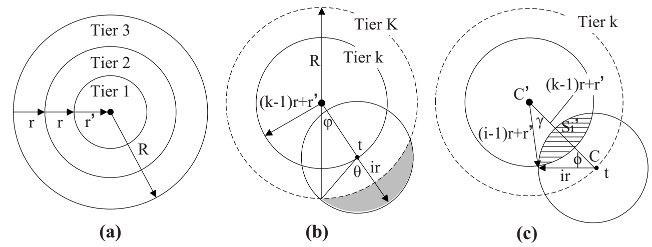

Fig. 2: (a) An illustration of a three-tier network. (b) Shadow zone: the sub-area of the disk C outside the reader's coverage. (c) Overlap of C and C'.

$$\chi(n') = f(1 - (1 - \frac{1}{f})^{n'}), \tag{4}$$

where f is the frame size. Hence, in the ith frame, the tag t needs to keep active to monitor $f - \chi(p|\Gamma_{i-1} \cup \Gamma'_{i-1}|)$ slots for checking whether or not these slots are busy, where $i \geq 1$, $\Gamma'_0 = \emptyset$, $\Gamma_0 = \{t\}$, and p is the probability whether to participate in the building of the status bitmap. Take a close look at Γ'_i. It is actually the tag set that resides within the disk C' that takes the reader's position as the center and the distance $r' + (i-1)r$ as the radius. Thus, we have:

$$|\Gamma'_i| = \rho \times S'_c = \rho \times \pi(r' + (i-1)r)^2, \tag{5}$$

where S'_c is the area of the disk C'. Similarly, the tag set Γ_i is actually the tag set that resides within the disk C that takes the tag t's position as the center and the distance $i \times r$ as the radius. Considering the reader's coverage, we have:

$$S_c = \begin{cases} \pi(ir)^2, & if\ k+i-1 \leq K, \\ \pi(ir)^2 - S_i, & otherwise, \end{cases} \tag{6}$$

where S_c is the area of the disk C within the reader's coverage and S_i is the sub-area (the shadow zone shown in Fig. 2(b)) of the disk C beyond the reader's coverage, which is:

$$S_i = \theta \times (ir)^2 + \psi \times R^2 - \sin\psi \times Rr_0, \tag{7}$$

where

$$\begin{cases} r_0 = r' + (k-1)r \\ \psi = \arccos \frac{R^2 + r_0^2 - (ir)^2}{2Rr_0} \\ \theta = \pi - \arccos \frac{r_1^2 + (ir)^2 - R^2}{2r_0(ir)}. \end{cases}$$

With S_c, we have:

$$|\Gamma_i| = \rho \times S_c. \tag{8}$$

The union $\Gamma_i \cup \Gamma'_i$ is the tag set located at the area S'_c or S_c. If these two areas do not overlap (when $i \leq \frac{k}{2}$ holds), we have $|\Gamma_i \cup \Gamma'_i| = |\Gamma_i| + |\Gamma'_i|$. On the contrary, if these two areas overlap ($i > \frac{k}{2}$), as shown in Fig. 2(c), we are not supposed to double count the tags in the overlap zone S'_i (shadow zone). According to Fig. 2(c), we can derive S'_i as follows:

$$S'_i = \gamma \times r_1^2 + \phi \times r_2^2 - \sin(\gamma+\phi)r_1r_2, \qquad (9)$$

where

$$\begin{cases} r_1 = (i-1)r + r' \\ r_2 = (k-1)r + r' \\ \gamma = \arccos\frac{r_1^2+(ir)^2-r_2^2}{2r_1r_2} \\ \phi = \arccos\frac{r_1^2+(ir)^2-r_2^2}{2(ir)r_2}. \end{cases}$$

Hence, we have:

$$|\Gamma_i \cup \Gamma'_i| = \begin{cases} \rho(S_c + S'_c), & if\ i \le \frac{k}{2}, \\ \rho(S_c + S'_c - S'_i) & if\ i > \frac{k}{2}. \end{cases} \qquad (10)$$

Consider K frames in K rounds. The total number of slots that the tag takes to receive something is $\sum_{i=0}^{K-1}(f - \chi(p|\Gamma_i \cup \Gamma'_i|) = \sum_{i=0}^{K-1} pf(1-\frac{1}{f})^{|\Gamma_i \cup \Gamma'_i|}$. In addition, the tag t also needs to receive the indicator vector and execute the checking frame in each round. Adding up all these overhead, we have the total number $\mathcal{N}_r$ of slots monitored by the tag:

$$\mathcal{N}_r = \sum_{i=0}^{K-1} pf(1-\frac{1}{f})^{|\Gamma_i \cup \Gamma'_i|} + K\lceil\frac{f}{96}\rceil + K \times L_c. \qquad (11)$$

We now analyze the number of transmission slots. In the first round, the tag t will decide with probability p whether to participate in the status bitmap. If the answer is positive, it gives a one-bit response in its picked slot. After that, in the following rounds, the tag will transmit a message in the slots that are picked by the newly found tags in the $(i-1)$th round and also have not been relayed by tag t nor proven to be busy by the reader. Specifically, the tags in $\Gamma_{i-1} - \Gamma_{i-2}$ are the tag set that is newly found by tag t in the $(i-1)$th round. At the end of the $(i-1)$th round, the reader will broadcast the indicator vector to refrain the information flooding. Hence, the tags belonging to $\Gamma_{i-1} \cup \Gamma'_{i-1}$ will go to sleep; only the left tags in $\Gamma_{i-1} - \Gamma_{i-2} - \Gamma'_{i-1}$ are likely to pick the slots that have not been relayed. Hence, we have the expected number $\mathcal{N}_{s,i}$ of transmission slots in the ith round:

$$\mathcal{N}_{s,i} = \begin{cases} p, & if\ i = 1, \\ \chi(\mu_i)(1 - \frac{\chi(p|\Gamma_{i-1} \cup \Gamma'_{i-1}|)}{f}), & if\ i \ge 2, \end{cases} \qquad (12)$$

where $\mu_i = p|\Gamma_{i-1} - \Gamma_{i-2} - \Gamma'_{i-1}|$. Besides $\mathcal{N}_{s,i}$, the tag also needs to transmit messages in the checking frame. Since this overhead is negligible compared with the f-slotted frame, we just take the upper bound K as the expected number of transmission slots in the checking frame. Hence, we have the total number of transmissions slots:

$$\mathcal{N}_s = \sum_{i=1}^{K} \mathcal{N}_{s,i} + K \times L_c. \qquad (13)$$

If multiple sessions of communications are required for ensuring estimation accuracy, the total execution cost in a networked tag system can be derived by adding up all execution time or energy overhead in each communication.

V. Missing-tag Detection in Networked Tag Systems

A. Traditional Missing-tag Detection

Missing-tag detection is to determine whether or not some tags in the system are missing. A missing-tag detection protocol is subject to the following requirement: a single execution of the protocol reports the missing event with a probability δ if more than m tags are missing. Formally:

$$\forall i > m : Prob\{A \mid \mathcal{E}(i)\} \ge \delta, \qquad (14)$$

where A is the event that the protocol reports a missing tag event, and $\mathcal{E}(i)$ is the event that i tags are missed.

In a traditional RFID system, the seminal work of Trusted Reader Protocol (TRP) proposed by Tan et al. [8] works as follows: The reader initiates missing-tag detection by broadcasting a request (f, η) to tags under its coverage. The request is followed by a time frame consisting of f slots, each of which carries one bit information. Upon receiving the request, a tag pseudo-randomly picks a slot (by hashing its ID together with the random seed η) in the time frame and transmits during that slot. A slot is said to be *empty*, *singleton*, or *collision* if no tag transmits, exactly one tag transmits, or more than one tag transmits in the slot. A singleton or collision slot is also called a *busy* slot. The reader monitors the time frame and turns the status of each slot into a status bitmap of f bits, where a busy slot corresponds to a bit '1' and an empty slot corresponds to a bit '0'.

With the knowledge of all tag IDs as a priori, the reader can predict which slots should be busy and which should be empty. If a would-be busy slot turns out to be empty (corresponding to '0' in the status bitmap), any tag that picks this slot must be missing. Subject to the requirement (14), TRP sets the smallest frame size f to minimize the execution time. Multiple executions of TRP will further increase the detection probability.

B. Applying TRP in Networked Tag Systems through CCM

We show that the CCM model can enable TPR for missing-tag detection in networked tag systems. Each communication including K rounds in CCM corresponds to a single execution of TRP in the traditional RFID system. The reader initiates a round by broadcasting the detection request with parameters (f, η) through CCM. After receiving the request, a tag randomly picks a slot in the frame to transmit. In the following frames (rounds), the tag will retransmit the bitmaps received in the preceding frame. If the reader receives nothing from the checking frame, it terminates the current communication and advances the next execution of missing-tag detection. The reader will collect multiple bitmaps from tier-1 tags. It produces the final status bitmap by combining all individual bitmaps with bitwise OR.

C. Execution Time and Energy Overhead

Given the frame size f and the number K of tiers, the performance analysis of TPR is identical to that of GMLE except that $p = 1$ (the probability that a tag determines whether or not to participate in the status bitmap).

VI. Numerical Evaluation

In this section, we evaluate the performance of CCM, in terms of the energy cost and the execution time.

A. System Setting

There is no prior literature on RFID estimation and missing-tag detection for networked tag systems. The only method known to work in such systems is through ID collection; once all tag IDs are collected, we can count or check whether any tags are missing. The only ID collection protocols for networked tags are the Contention-based ID Collection Protocol (CICP) and Serialized ID Collection Protocol (SICP), among which SICP works better [16]. In our simulations, we use SICP as the benchmark for performance comparison, and evaluate the performance of GMLE and TPR in networked tag systems under the proposed CCM. Three performance metrics are used: 1) execution time measured by the number of time slots, each carrying one or more bits, 2) number of bits sent per tag, and 3) number of bits received per tag. The last two are indirect measurements of energy cost.

In the simulations, all tags are randomly distributed within a disk $\mathbb{C}$ with a radius of 30m. The reader is located at the center of $\mathbb{C}$ and the reader-to-tag communication range R is set to 30m. The tag-to-reader communication range r' is set to 20m. There are $n = 10,000$ networked tags under the reader's coverage. Hence, the tag density over this area is $\rho = \frac{10,000}{\pi \times 30^2} \approx 3.54$. For each tag, we vary its inter-tag communication range r from 2m to 10m at a step of 1m, complying with the range of prototype networked tags described in [19]. The reason why we do not let $r = 1$ is that it is too small to form a connected network among tags under the above tag density ($\rho = 3.54$). Any data output in the simulations is the average result of 100 individual trials. Note that, unlike our communication model, the reader's request in SICP may reach at the tags via multiple transmissions. We let the communication ranges from the reader to tier-1 tags, or vice versa, be r' when conducting the simulation of SICP. Under above parameter settings, Fig. 3 shows the number of tiers with respect to the inter-tag communication range r. As expected, the number decreases as r increases.

B. Performance Comparison

We compare the performance of SICP in networked tag systems, GMLE-based RFID estimation [28] through CCM (GMLE-CCM), and TRP-based missing tag detection [8] through CCM (TRP-CCM), in terms of the execution time and energy cost. For RFID estimation, the confidence level α is set to 95%, and the relative error β is set to 5%. According to [28], the optimal sampling probability that each tag participates in a frame is $p = \frac{1.59f}{n} = 1.59f \times 10^{-4}$ and the frame size f is set to 1671 in order to meet the accuracy requirement. For the missing tag detection, the detection probability δ is set to 95%, and the missing tolerance m is set to $0.005n = 50$. Based on the parameter configuration specified in [8], we derive the smallest frame size $f = 3228$ that meets the detection accuracy δ. With above settings, we evaluate the performance of RFID estimation and missing-tag detection in networked tag systems.

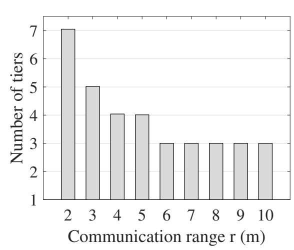

Fig. 3: Number of tiers.

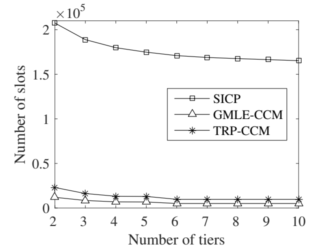

Fig. 4: Execution time.

1) Execution Time: Fig. 4 studies the time efficiency of different approaches under various inter-tag communication ranges r. We measure the time efficiency by the number of time slots rather than the actual execution time in the unit of second. The reason is that the RFID Gen2 standard [29] just specifies a time interval of each slot but not gives an exact value. It is more straightforward to use the number of slots. As shown in Fig. 4, GMLE-CCM and TRP-CCM take much fewer slots than SICP, meaning that CCM makes the system-level functions work more efficiently in a networked tag system. Specifically, GMLE-CCM and TRP-CCM cut the time by an order of magnitude when comparing with SICP. For example, when $r = 6$, the number of slots in SICP is 170,926, whereas those numbers in GMLE-CCM and TRP-CCM are just 5076 and 9747 — 97.0% and 94.3% reduction, respectively. Note that the execution time decreases as r increases. That is because a large value of r lowers the number of tiers, such that the wave of tag information will flow through the entire network with fewer hops, saving the communication time. In addition, during the execution of SICP, one third of slots are used for tag ID transmissions, which are much longer than most short slots that carry only one single bit in GMLE-CCM and TRP-CCM. If taking the length difference of time slots into account, the performance gap between SICP and CCM-based protocols will further widen.

2) Energy Cost: Now we measure the energy cost of CCM-based solutions by the number bits sent per tag and the number of bits received per tag.

a) Maximum Number of Bits: Table I and Table II show the maximum numbers of bits sent and received by any tag in the networked tag system, respectively. In Table I, the maximum numbers of bits sent by any tag in GMLE-CCM and TRP-CCM are much smaller than that in SICP. For example, when $r = 6$, the number of slots SICP takes is 9002, whereas those numbers in GMLE-CCM and TRP-CCM are just 42.0 and 120.9, reducing by about two orders of magnitude. This great performance boost is because that a slot's status can be converged to the reader in a benign way and the slot will not be taken into account by the tag once it is relayed by the tag or silenced by the indicator vector broadcast by the reader. This improvement allows the networked tags to save more energy

TABLE I: MAXIMUM NUMBER OF SENT BITS.

	Maximum number of bits sent per tag				
	r = 2	4	6	8	10
SICP	41767	17907	9002	5956	5593
GMLE-CCM	28.0	34.8	42.0	49.3	53.6
TRP-CCM	73.3	93.9	120.9	145.0	164.7

TABLE II: MAXIMUM NUMBER OF RECEIVED BITS

	Maximum number of bits received per tag				
	r = 2	4	6	8	10
SICP	516174	385927	376235	420863	477507
GMLE-CCM	15903	9663	7597	7563	7327
TRP-CCM	30968	18940	14981	14873	14714

TABLE III: AVERAGE NUMBER OF SENT BITS.

	Average number of bits sent per tag				
	r = 2	4	6	8	10
SICP	720.1	514.6	456.8	434.3	417.4
GMLE-CCM	9.3	12.9	17.3	23.5	27.9
TRP-CCM	28.4	39.8	56.3	76.9	96.6

TABLE IV: AVERAGE NUMBER OF RECEIVED BITS.

	Average number of bits received per tag				
	r = 2	4	6	8	10
SICP	218171	179196	198332	245074	303964
GMLE-CCM	15887	9648	7578	7539	7300
TRP-CCM	30916	18890	14919	14793	14618

for longer execution of the system-level applications. Note that, the overhead of GMLE-CCM and TRP-CCM increases with r. The reason is that large r makes Γ_i contain more tags within the i-hop transmissions to a tag, which places more burden on the tag for relaying the data from these tags.

Table II presents the maximum number of bits received by any tag in the networked tag system. Compared to SICP, GMLE-CCM and TRP-CCM reduce this overhead by more than one order of magnitude. For example, when $r = 6$, the overhead of SICP is $376,235$, while those numbers in GMLE-CCM and TRP-CCM are only 7597 and 14981, respectively. This significant performance improvement is due to collision-enabled data fusion in CCM. We observe that the overhead of GMLE-CCM and TRP-CCM decreases with r. That is because, the larger r is, the smaller the number of tiers is, which thereby reduces the number of rounds needed for one-session communication throughout the network.

b) Average Number of Bits: Table III and Table IV show the average numbers of bits sent and received per tag in the networked tag system, respectively. Similar to above results in Table III and Table IV, GMLE-CCM and TRP-CCM are far superior to SICP. For example, when $r = 6$, GMLE-CCM and TRP-CCM drop the average number of bits sent per tag from 456.8 to 17.3 and 56.3, as shown in Table III. The average numbers of bits received per tag are reduced to 7578 and 14919, respectively. Compared with 198,332 bits, our model saves more than 90% energy cost.

Since the energy consumption for most RF transmitters, e.g., CC1120 [30], in RX mode and TX mode are similar or in the same order of magnitude, the much larger number of bits received per tag plays a dominant role in the energy cost. Hence, by taking both transmission and reception overhead of Table III and Table IV into consideration, we conclude that GMLE-CCM and TRP-CCM can reduce each tag's energy cost by more than one order of magnitude than SICP. In addition, the maximum overhead of CCM is almost the same as the average overhead. For instance, when $r = 6$, the maximum number of bits received by a tag in GMLE-CCM is 7597, which is very close to the average number 7578. This small difference well indicates that CCM is a great load-balanced communication model that is able to prolong the lifetime of the entire network.

VII. Related Work

We review the existing work on RFID estimation and missing-tag detection, which have been used as the test cases for demonstrating how to apply CCM in networked tag systems to implement system-level functions. Besides, we also review the recent work on the design of networked tags and introduce the only ID-collection protocols tailored to the networked tags.

The problem of *RFID estimation* [2]–[7] is to estimate the number of tags in a certain area covered by readers. It is a basic function that can be used to monitor the inventory level in a warehouse, the sales in a retail store, and even the popularity of attractions in tourism [4]. It can also serve as a pre-processing step to make other functions (such as tag identification [31]) more efficient. The function of *missing-tag detection* enables automatical detection of unexpected absence of tagged objects in a large storage space (e.g., warehouse or retail store), which may otherwise have to be performed manually and frequently in order to catch any missing event such as theft in time.

Kodialam and Nandagopal [5] estimate the number of tags in an RFID system based on the probabilistic counting methods [32]. The same authors propose a non-biased follow-up work in [6]. Han et al. [7] improve the performance of [5]. Qian et al. [2] present the Lottery-Frame scheme (LoF) for estimating the number of tags in a multiple-reader scenario. The above work focuses on time efficiency. Energy-efficient RFID protocol design is in general under-studied.

Tan et al. [8] propose a Trust Reader Protocol (TRP) for probabilistic missing-tag detection. Their follow-up work [9] probabilistically identifies missing tags (or unknown tags) in the system. However, it cannot ensure that all missing tags (or unknown tags) are identified. In addition, the proposed methods deal with missing tags and unknown tags separately, and will not work when they both exist. Sato et al. identify missing tags with group coding [10]. Luo et al. [11] reveal the tradeoff relationship between time efficiency and energy efficiency and consider these two performance metrics in their design of missing-tag detection protocols.

Networked tags are in their nascent stage of development. M. Gorlatova et al. [19] design and prototype the first networked tag, with its network model similar to the traditional sensor network and its communication model being CSMA. V. Liu et al. [20] present the design of a communication system that enables two devices to communicate using ambient

RF as the only source of power. They leverage existing TV and cellular transmissions to eliminate the need for wires and batteries, thus enabling ubiquitous communication where devices can communicate among themselves. Z. Shen et al. [21] investigate a unique phase cancellation problem that occurs in backscatter-based tag-to-tag communication systems. Y. Karimi et al. [22] propose a novel architecture of the demodulator that is able to demonstrate a longer range in tag-to-tag communication networks.

In spite of this advancement, there is no prior work on RFID estimation and missing-tag detection in the context of networked tags. The only ID collections for networked tag systems were proposed in [16], which first uses a system-wide broadcast to establish a spanning tree for routing, and then uses CSMA to relay IDs hop by hop to the reader. However, it has been well established in RFID research that performing system-level functions by collecting all tags' IDs is very inefficient [5], [8]. This will be even more true in a state-free networked-tag system.

VIII. Conclusion

This paper is the first study on the design of a new communication model tailored to system-level functions in emerging networked tag systems. We propose a Collision-resistant Communication Model (CCM) that uses collision in tag communications to merge the data from different tags on their way towards the reader. By repeating multiple rounds, the data are transmitted tier by tier across the tag network, without any inter-tier interference. We further use two important applications, RFID estimation and missing-tag detection, to demonstrate how traditional protocols can be applied in networked tag systems through CCM. Simulation results show that these applications under CCM greatly outperform the alternative ID-collection approach, in terms of execution time and energy cost.

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