P-MTI: Physical-Layer Missing Tag Identification via Compressive Sensing

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***Abstract*—Radio frequency identification (RFID) systems are emerging platforms that support a variety of pervasive applications. RFID tags can be used to label items and enable item-level monitoring. The problem of identifying missing tags in RFID systems has attracted wide attention due to its practical importance (e.g., anti-theft). This paper presents P-MTI: a Physical-layer Missing Tag Identification scheme that effectively makes use of the lower-layer information and dramatically improves operational efficiency. Unlike conventional approaches, P-MTI looks into the aggregated tag responses instead of focusing on individual tag responses and extracts useful information from physical-layer collisions. P-MTI leverages the sparsity of missing tag events and reconstructs tag responses through compressive sensing. We prototype P-MTI using the USRP software defined radio and Intel WISP platform. We also evaluate the performance of P-MTI with extensive simulations and compare to previous approaches. The experiment results show the promising performance of P-MTI in identification accuracy, time efficiency, as well as robustness over noisy channels.**

***Index Terms*—Compressive sensing, missing tag identification, radio frequency identification (RFID) systems.**

I. INTRODUCTION

RADIO frequency identification (RFID) systems are becoming important platforms that enable ultra-low-power ubiquitous computing [12], [26], [34], [41]. Passive RFID tags can harvest energy from high-power RF signals of a nearby RFID reader. A tag can backscatter or absorb the RF signals to send one-bit information in response to reader's interrogation. Due to the small form factor and low manufacturing costs of RFID tags, RFID systems make them ideal for massive object management in a variety of applications [13], [43]. Formally, the problem of missing tag identification can be defined as follows: Given a set of RFID tags under monitoring $\mathbf{N} = \{n_1, n_2, \ldots, n_N\}$, we want to identify the missing tags $\mathbf{K} \subseteq \mathbf{N}$ that are not in the interrogation zone.

The problem of missing tag identification has attracted wide attention due to its practical importance [20], [38]. For example, RFID tags can be attached to items as labels in a warehouse, and warehouse managers can monitor them for anti-theft purpose. Such a problem of item-level monitoring also appears in applications of healthcare, logistics, military, etc. One straightforward solution might be to identify all the tags and check whether anyone is missing using traditional RFID tag identification schemes [11], [29]. When the number of tags is small, such a method can frequently identify and monitor each tag. When the number of tags scales up, tag–tag collisions become increasingly severe and incur substantial collision arbitration overhead as well as the transmission overhead of tag IDs.

Recently, many probabilistic missing tag identification schemes [20], [38] try to identify missing tags without explicitly sending tag IDs. Due to the inherent nature of sequential lookup, those approaches consume a substantial number of time-slots that is linearly proportional to the total number N of tags. Despite many advances, such approaches largely overlook the physical-layer information and solely rely on upper-layer information, rendering them less efficient for real-time monitoring.

The compelling practical demands and the inadequacy of the status quo motivate the design of more efficient missing tag identification schemes. In this paper, we present Physical-layer Missing Tag Identification (P-MTI), which efficiently utilizes the physical-layer information of tag responses and thereby substantially improves the monitoring efficiency. Unlike conventional approaches focusing on individual tag responses, we look into the aggregated signals from concurrent tag responses which provide us much richer information.

Say that we wish to identify K missing tags out of N, where $N \gg K \geq 0$. We let each tag i transmit a sequence of M random bits A_i concurrently with other tags. Each tag i transmits one bit of A_i at each time-slot. The tags modulate the bits into physical-layer symbols using on–off keying. In the physical layer, the transmitted symbols from multiple tags will mix in the air and arrive at the reader as PHY symbol superpositions. In the jth time-slot, the reader receives $y_j = \sum_{i=1}^{N} A_i(j)$, and thus after M time-slots, the received symbols at the reader $\mathbf{y}$ can be concisely represented as $\mathbf{y} = \mathbf{A}\mathbf{x}$, where $M \times N$ matrix $\mathbf{A} = [A_1, A_2, \ldots, A_N]$. $\mathbf{y}$ denotes an $M \times 1$ vector where each entry represents one of the M PHY symbol measurements. $\mathbf{x}$ denotes an $N \times 1$ binary vector where the nonzero entries indicate presence of tags, while the zero entries imply the missing tags. For ease of presentation, here we omit channel coefficients. To compute $\mathbf{x}$ and figure out the K zero entries, generally we need $M = N$ measurements. As a matter of fact, it suffices for identifying the missing tags to know the differential of two consecutive instances, $\mathbf{x}_\Delta = \mathbf{x}_t - \mathbf{x}_{t-\Delta}$. A nonzero entry in $\mathbf{x}_\Delta$ indicates that the corresponding tag is present in the former

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measurement while absent in the latter measurement, which implies a missing tag event. Thus, we only need to reconstruct $\mathbf{x}_\Delta$ to identify the missing tags that are missed during the period $[t-\Delta, t]$. Moreover, we know that the missing tag events are inherently sparse, i.e., $N \gg K \geq 0$. Therefore, $\mathbf{y}_\Delta = \mathbf{A}\mathbf{x}_\Delta$ can be formulated as a standard compressive sensing problem, which allows us to recover $\mathbf{x}_\Delta$ with only a substantially smaller number of measurements. The tags that are missed during the time $[0, t-\Delta]$ can be identified by examining $\mathbf{x}_{t-\Delta} - \mathbf{x}_0$ in a similar manner.

We implement a prototype system and validate P-MTI based on the Universal Software Radio Peripheral (USRP) software defined radio with the Intel Wireless Identification and Sensing Platform (WISP) computational RFID tags. We also investigate our approach in large-scale settings with extensive simulations compared to existing approaches [20], [38]. The experiment results show that the proposed P-MTI scheme significantly improves the time efficiency. In particular, P-MTI can effectively reduce the communication time by approximately 64% over state-of-the-art approaches. The improvement stems from both the efficient use of lower-layer information and the compressive sensing-based reconstruction.

The contributions of this paper are briefly summarized as follows. For the first time: 1) this paper presents the physical-layer missing tag identification scheme, which makes extensive use of lower-layer information in large-scale RFID systems; 2) exploiting the sparsity of missing tag events, the proposed scheme further improves missing tag identification efficiency with compressive sensing technique; 3) we consolidate our design with a prototype system using the software-defined RFID reader and the computational RFID tags.

The rest of this paper is organized as follows. We first describe the system model and introduce the problem of missing tag identification in Section II. We present detailed description on P-MTI in Section III. We describe the prototype implementation experience in Section IV. We conduct extensive simulations and analyze the results in Section V. We briefly review the related literature in Section VI. We conclude this paper in Section VII.

II. System Model and Problem Description

A. System Model

We consider an RFID system consisting of three main components: a large number of RFID tags attached to items under monitoring, one or more RFID readers that monitor the tags, and a back-end server that coordinates the readers through reliable links. Commercial RFID readers (e.g., Alien ALR 9900+ [1]) connect via RS232 or Gigabit Ethernet to PCs, which allows high throughput and low-latency communication. We focus on the communication between one RFID reader and a large number of tags rather than the back-end server. We also study parallel interrogation of multiple readers [38].

In this paper, we exclusively focus on the RFID system operating in the 900-MHz Ultra-High Frequency (UHF) band. An RFID reader transmits high-power radio frequency signals to energize RFID tags and initiates the interrogation. RFID tags backscatter or absorb the signals to communicate with the reader (i.e., on–off keying). Due to the constraints of transmission power, the communication bandwidth is generally narrow and thus can be mathematically modeled using a single complex number [31]. Following existing works [20], [31], [38], we assume that the uplink communication from tags to readers is synchronized by the readers. As the uplink data rate is low, the synchronization can be achieved in practice [31]. For simplicity, we assume that the wireless channel introduces only linear distortions. We plan to study the nonlinear scenario for future work. Such a system model has been adopted in many RFID systems following the *de facto* EPCglobal Gen-2 standard [3].

The EPCglobal Gen-2 standard [3] specifies several mandatory operations to regulate the RFID tags, while providing flexibility for RFID manufacturers to implement value-added features with available components (e.g., random number generator [3], lightweight hash function, etc.). We note that such routine components are widely implemented in current RFID tags.

In this paper, we do not consider the case of malfunctioning RFID tags. A malfunctioning tag may not respond to a reader's interrogation even within the communication range (due to many possible physical failures on the tag). As such, we treat every unresponsive tag as a missing tag. The unresponsive tags need to be identified and replaced in practical systems.

B. Problem Description

Consider an RFID system $\mathbf{N} = \{n_1, n_2, \ldots, n_N\}$ representing all the N tags covered by a reader, and $\mathbf{K} \subseteq \mathbf{N}$ representing the set of missing tags. The reader has the access to the IDs of the tags, among which K tags are missing. *The problem of missing tag identification is to identify the K missing tags*. The missing tag set may be empty meaning that all the tags in $\mathbf{N}$ are present. We denote by $|\cdot|$ the cardinality of a set, and thus $K = |\mathbf{K}|$ and $N = |\mathbf{N}|$. We particularly focus on the cases where $N \gg K \geq 0$. Although the reader has the knowledge of $\mathbf{N}$, the number of missing tags K is not known in advance. If most tags are missing and only a small number of tags are present, one may directly identify the present tags with collision arbitration schemes [27], [33]. Many recent cardinality estimation schemes [18], [21], [28], [42], [44] can be used to estimate the number of tags.

To ensure real-time monitoring, we need to reduce the processing time of missing tag identification and design a scalable scheme to support thousands or even more tags. As each tag has to transmit at least one-bit information to announce its presence, prior work believes that at least N time-slots are needed to monitor N tags [20]. Generally, such schemes sequentially look up individual tag responses and only differentiate the empty/singleton/collision slots, meaning that only $\log_2 3$ bits of information can be extracted per slot. Moreover, each tag transmits multiple physical-layer symbols to allow the reader to distinguish different types of slots.

To improve monitoring efficiency, we wish to make extensive use of physical-layer symbols by extracting more amount of information. On the other hand, as the tags are generally resource-constrained, we wish to make minimum modifications to the tags without introducing extra computation or communication overhead.

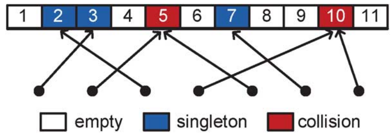

Fig. 1. Frame-slotted Aloha: Seven tags contend for 11 time-slots.

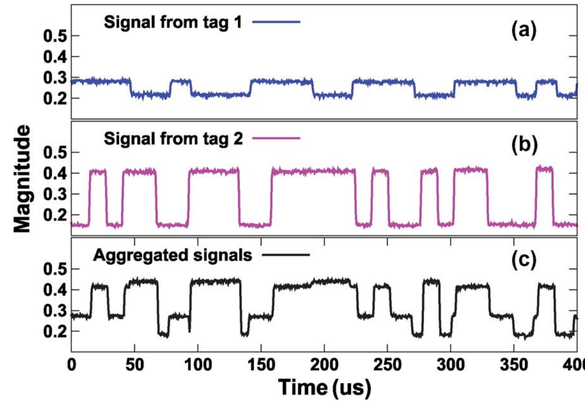

Fig. 2. Received signals at RFID reader: (a) signals from tag 1; (b) signals from tag 2; (c) aggregated signals from the two tags.

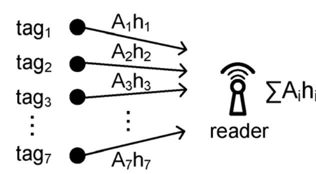

Fig. 3. Response signals from seven tags mix in the air and aggregate at the reader. If tag i is missing, then its contribution to the aggregated physical-layer symbols would be missing.

III. P-MTI Design

We first describe the rationale of P-MTI design in Section III-A. We present a basic solution that leverages the physical-layer information for missing tag identification in Section III-B. We then exploit the sparsity of missing tag events and use compressive sensing technique to enhance the missing tag identification efficiency in Section III-C. We enhance decoding robustness against noisy measurements in Section III-D. We present an operation overview of our approach in Section III-E. We finally discuss additional design considerations in Sections III-F and III-G.

A. P-MTI *Rationale*

The conventional schemes generally exploit the frame-slotted Aloha protocol to identify the missing tags [20], [38]. Fig. 1 illustrates an instance where seven tags contend for 11 time-slots. Say that one tag should have responded in a singleton slot (e.g., the seventh time-slot) if present, but no response is received from the time-slot. Then, the reader may infer the tag is missing. In such schemes, less information can be extracted from empty and collision slots. As each tag has to transmit at least one-bit information to announce its presence, prior work believes that at least N time-slots are needed to monitor N tags [20]. Although many advances have been achieved in missing tag identification [20], [38], existing approaches largely overlook the PHY information and extract a limited amount of information at the upper layer.

To fundamentally improve the protocol efficiency, we conduct initial experiments to explore the physical layer of RFID system using the USRP software defined radio and the WISP programmable tags. Section IV presents the implementation and experiment settings in detail. A PHY symbol can be represented as a complex number (amplitude and phase components). As RFID backscatter communication uses on–off keying (a simple amplitude-shift keying scheme), at physical layer an RFID reader decodes tag responses by measuring only amplitude and ignoring phase component [3]. We note that such on–off keying is compatible with existing RFID modulation schemes as specified in the C1G2 standard. Fig. 2(a) shows the magnitude of backscatter signals received at the USRP reader when one WISP tag (tag 1) transmits a sequence of pseudo random bits using on–off keying. Similarly, Fig. 2(b) depicts the signals from tag 2. The magnitude of received signals depends on the wireless channel attenuation. The reader can decode tag 1 and tag 2 individually when no collision occurs. When both tags transmit at the same time [Fig. 2(c)], we find that the aggregated PHY symbols exhibit as the superposition of the symbols from both tags. When more tags respond concurrently, the responsive signals from multiple tags similarly exhibit as a sum when they arrive at the reader. We propose to efficiently utilize the aggregated signals from concurrent tag responses (which were previously treated as collision slots) and present P-MTI, which makes extensive use of such physical-layer information.

The rationale behind P-MTI is that the missing tags reveal themselves by the absences of responses. Say that there are seven tags (i.e., tags 1–7), and we let them send random bits concurrently as in Fig. 3. The responses from tags mix in the air and aggregate at the reader. The reader will receive physical-layer symbols from all the seven tags if none is missing. If any tags are missing, the received symbols may differ from the expected ones. We denote the symbols of tag i as A_i, and denote the channel coefficient as h_i. The aggregated physical-layer responses received by the reader can be represented as $\sum_{i=1}^{7} A_i h_i$. If tag k is missing, the aggregated responses become $\sum_{i=1}^{7} A_i h_i - A_k h_k$. We can thus leverage the differences of physical-layer symbols to detect and identify the missing tags. Departing from conventional schemes that look at individual tag response at each slot, P-MTI allows multiple tags to concurrently respond in each time-slot, which fundamentally improves the protocol efficiency.

B. *Physical-Layer Missing Tag Identification: A Basic Solution*

In P-MTI, an RFID reader initiates the missing tag monitoring by broadcasting an operation code. When receiving the command, each tag generates random bits using a pseudo random number generator with its ID as the seed. The pseudo random bits of tag i are denoted as $\mathbf{A}_i$, an $M \times 1$ bit vector. At each time-slot, each tag backscatters radio frequency signals if the random bit turns out to be 1, or keep silent otherwise. The physical-layer symbols from N tags mix in the air and aggregate at the reader. We model the RFID communication channel with a complex matrix $\mathbf{H}_{N\times N}$. Then, the aggregated symbols at the reader can be represented as follows:

$$\mathbf{y} = \mathbf{AHx} \tag{1}$$

where $\mathbf{y}$ is an $M\times 1$ complex vector representing the aggregated symbols, $\mathbf{A}$ is an $M \times N$ binary matrix, and $\mathbf{x}$ is an N-entry binary vector with nonzero (zero) entries representing presence (absence) of tags. As the backscatter communication is generally within a narrow wireless band [31], the wireless channel between each tag and the reader can be mathematically modeled with a complex number, incorporating both signal attenuation and phase shift of wireless channel [31]. Therefore, we assume $\mathbf{H} = \mathrm{diag}(h_1, h_2, \ldots, h_N)$, where h_i denotes the channel coefficient from tag i to the reader. Thus, $\mathbf{Hx}$ can be represented with an $N \times 1$ complex vector $\mathbf{z}$, where the ith entry $z_i = h_i x_i$ [31]. As $\mathbf{x}$ is a binary vector, we have $z_i = h_i$ if $x_i = 1$, and $z_i = 0$ otherwise. Hence, (1) can be rewritten as follows:

$$\mathbf{y} = \mathbf{Az}. \tag{2}$$

Since the reader has access to the tag IDs through database lookups, the reader can generate the pseudo random binary matrix $\mathbf{A}$ using the same random number generator with the tags IDs as seeds. Therefore, we can compute $\mathbf{z}$ by solving the linear equation (2) with the knowledge of $\mathbf{y}$ and $\mathbf{A}$. The nonzero entry $z_i = h_i$ is the channel coefficient between tag i and the reader. A zero entry in $\mathbf{z}$ indicates that the corresponding tag is missing. In such a way, P-MTI not only identifies missing tags, but also measures the channel coefficients $\mathbf{H}$ between present tags and the reader.

To solve the linear equation (2), we need N measurements of physical-layer symbols since the unknown $\mathbf{z}$ is an $N \times 1$ vector. As the reader does not need to distinguish empty/singleton/collision slots, the tags do not need to transmit multiple physical-layer symbols in each slot, which further reduces the transmission time.

C. Compressive Sensing-Based Recovery

We notice that P-MTI needs N measurements per monitoring operation. In practical scenarios, one may need to frequently run the missing tag identification protocol to ensure a timely report of missing tag events.

As a matter of fact, it suffices to compute the differential of aggregated responses between two consecutive instances to achieve continuous monitoring. The rationale is straightforward: If a response from a tag is detected while no more response is detected later from the tag, then the tag is probably missing. We therefore compute the differential of the aggregated responses between two consecutive instances at time t and $t - \Delta$, $\mathbf{y}_\Delta = \mathbf{y}_t - \mathbf{y}_{t-\Delta}$, and infer the dynamics of the tags. From (2), we have

$$\mathbf{y}_\Delta = \mathbf{y}_t - \mathbf{y}_{t-\Delta} = \mathbf{Az}_t - \mathbf{Az}_{t-\Delta}. \tag{3}$$

We refer the differential of $\mathbf{z}$ similarly by $\mathbf{z}_\Delta = \mathbf{z}_t - \mathbf{z}_{t-\Delta}$. Then, from (3), we have

$$\mathbf{y}_\Delta = \mathbf{Az}_\Delta. \tag{4}$$

Ideally, the zero entries in $\mathbf{z}_\Delta$ imply that corresponding tags are present, while the nonzero entries indicate that the tags are missing during the period $[t - \Delta, t]$. The tags that are missed during the time $[0, t-\Delta]$ can be identified by examining $\mathbf{z}_{t-\Delta} - \mathbf{z}_0$ in a similar manner. In practical RFID systems, the number of missing tags K is typically much smaller than the number of tags under monitoring N during a short monitoring interval, i.e., $N \gg K \geq 0$ [20], [38]. In other words, $\mathbf{z}_\Delta$ is K-sparse, meaning that there are at most K nonzero entries in $\mathbf{z}_\Delta$ [14]. According to the theory of compressive sensing, the K-sparse vector $\mathbf{z}_\Delta$ can be accurately recovered with only $M = O(K \log(N/K))$ measurements, by solving the following convex optimization problem [14]:

$$\begin{aligned} \text{Minimize:} \quad & \|\mathbf{z}_\Delta\|_{\ell_1} \\ \text{Subject to:} \quad & \mathbf{Az}_\Delta = \mathbf{y}_\Delta \end{aligned} \tag{5}$$

where $\|\cdot\|_{\ell_p}$ denotes ℓ_p-norm, i.e., $\|\mathbf{x}\|_{\ell_p} \triangleq \left(\sum_{i=1}^{i=N} |x_i|^p\right)^{1/p}$. Intuitively, the objective function of minimizing $\|\mathbf{z}_\Delta\|_{\ell_1}$ incorporates the fact that $\mathbf{z}_\Delta$ is sparse, while the constraint function is self-explanatory. Therefore, we can refer to convex optimization solvers (e.g., CVX [2], ℓ_1-Magic [6]) to compute $\mathbf{z}_\Delta$. In our implementation, we use the CVX solver [2] based on the interior-point algorithm [8]. It has been reported that $M = 3K \sim 4K \ll N$ measurements suffice to recover the K-sparse vector [23]. The number of missing tags K, however, is not known in advance. We set the number of measurements as $M = CK_{\mathtt{Max}} \log(N)$ in practice, where $K_{\mathtt{Max}}$ represents the estimated maximum number of missing tags and C is a constant. Our experiment results show that M measurements of physical-layer symbols are sufficient to reconstruct the K-sparse vector of $\mathbf{z}_\Delta$. When the number of missing tags exceeds the estimated maximum number $K_{\mathtt{Max}}$, our approach can identify at least $K_{\mathtt{Max}}$ missing tags, which allows P-MTI to adjust $K_{\mathtt{Max}}$ (Section V).

Leveraging the differential of aggregated responses, we improve the performance of P-MTI from $O(N)$ to $O(K \log(N/K))$. The compressive sensing-based information reconstruction allows us to extract the missing tag events directly from the differential of aggregated physical-layer symbols, thereby significantly reducing the required total time-slots compared with the existing schemes. Moreover, unlike existing schemes that need multiple physical symbols per slot, P-MTI needs only one symbol per time-slot. Therefore, the performance gain of such joint optimization is promising.

D. Enhancement Against Noisy Measurement

The above analysis ignores the noise in measurements. Wireless channel is mostly error-prone, subjected to various factors, such as interference, quantization, etc. [9]. Channel dynamics may also introduce noise to the measurements. Without robustness enhancement against noise, a detection system may result in unfavorable false alarms over noisy channels [17]. In the following, we enhance P-MTI's robustness against noise based on the theory of stable recovery [10]. Incorporating the noise, (4) can be rewritten as follows:

$$\mathbf{y}_\Delta = \mathbf{Az}_\Delta + e \tag{6}$$

where e denotes the error due to noise. Then, the optimization problem with relaxed constraints for recovery of $\mathbf{z}$ can be written as follows:

$$\begin{aligned} &\text{Minimize:} \quad \|\mathbf{z}_\Delta\|_{\ell_1} \\ &\text{Subject to:} \quad \|\mathbf{A}\mathbf{z}_\Delta - \mathbf{y}_\Delta\|_{\ell_2} \le \epsilon \end{aligned} \tag{7}$$

where the magnitude e is bounded by ϵ, i.e., $\|e\|_{\ell_2} \le \epsilon$. The theory of stable recovery [10] tells us that the solution $\hat{\mathbf{z}}_\Delta$ to the convex optimization problem (7) is a good approximation of $\mathbf{z}_\Delta$, and $\|\mathbf{z}_\Delta - \hat{\mathbf{z}}_\Delta\|_2 \le c\epsilon$ where c denotes a small constant. In other words, a small error in $\mathbf{y}_\Delta$ only slightly influences reconstruction of $\mathbf{z}_\Delta$. In order to identify missing tags, P-MTI only needs to distinguish the zero and nonzero entries in $\mathbf{z}_\Delta$. The noise may disturb $\mathbf{z}_\Delta$ and render the zero entries in $\mathbf{z}_\Delta$ nonzero (yet remaining small), affecting the detection accuracy. As the error is well bounded by the noise in practice, if the noise is small, we can use a threshold θ to accurately classify the contaminated signals with high probabilities. In particular, we define the detection function $f(z_{\Delta i})$ for tag i as follows:

$$f(z_{\Delta i}) = \begin{cases} \text{Present}, & \text{if } \|z_{\Delta i}\|_{\ell_2} < \theta \\ \text{Absent}, & \text{otherwise.} \end{cases} \tag{8}$$

If the magnitude of $z_{\Delta i}$ is smaller than θ, then tag i is present; otherwise, we say tag i is absent. When the channel condition dramatically deteriorates, the RFID reader cannot always accurately identify the missing tags. In such scenarios, the reader may use the basic P-MTI to identify the missing tags and monitor the channel $\mathbf{H}$. If the channel becomes reasonably good and stable, P-MTI can switch back to monitor the differential and identify the missing tags. The reader may also increase transmission power to increase the signal strength of backscatter responses, reduce data rates to enhance robustness against noise, and notify coexisting wireless devices to mitigate interferences. Although our approach cannot magically fight against strong channel variation (due to intentional inference, tag mobility, dramatic environment changes), P-MTI is experimentally proven to be robust in reasonably good channel conditions (Section V) and stationary environments (Section IV).

E. Operation Overview

Tag Overview: When receiving P-MTI command, each tag generates random bits with its ID as the seed and backscatters signals if the random bit is 1, or keeps silent otherwise. Each tag repeats the transmission until the reader terminates the interrogation.

Reader Overview: The reader initiates one monitoring operation by broadcasting P-MTI command to tags. The reader then measures $M = O(K \log(N/K))$ PHY symbols before terminating the interrogation. The reader decodes the PHY measurements by solving the optimization problem (7) and detects missing tags with $f(z_{\Delta i})$ as in (8). We discuss parameter settings in Section V.

F. Multiple Readers

Multiple readers are normally deployed to ensure a full coverage of a large monitoring area [38] due to power constraints, interrogation environment, etc. For instance, current RFID readers can only power up the passive RFID tags within approximately 10 m [1], [9], [32]. With more RFID readers, the number of tags in each monitoring area can be reduced, which mitigates the tag–tag contention and collision in the area. Moreover, the RFID readers with nonoverlapping coverage can interrogate tags in parallel without the reader–reader interference. Here, we explicitly assume that the tags under the coverage of each reader are known to the reader, and multiple readers monitor the tags and identify missing tags in parallel. Thus, an RFID reader only needs to coordinate with its immediate neighbor readers and identify the missing tags with the compressive sensing technique.

Recent works propose to efficiently schedule multiple RFID readers to improve the performance [38]. P-MTI is able to adopt similar coordination strategies to achieve the parallel interrogation of multiple readers. We note that a tag can be in the overlapped coverage of multiple RFID readers. As the readers with overlapped coverage can easily be scheduled into different time-slots by the server, the tags will only talk to one reader at a time. Therefore, each RFID reader with nonoverlapping coverage area can interrogate the tags in its coverage. Each RFID reader reports all the missing tags as well as the present tags in its coverage to the back-end server. The server claims a missing tag event only when a tag is absent in all the monitoring area of the RFID readers. Such a simple data processing task can be easily performed by powerful back-end servers.

G. Discussion

1) Communication Cost: The RFID reader needs to initiate the missing tag identification process by sending a command as well as communication parameters (e.g., data rate, encoding scheme, etc.). Such an initialization is typically in orders of milliseconds. As the RFID readers are normally connected with back-end server via high speed links, the communication cost between readers and back-end server is also small compared to that of the backscatter communication. The transmission time from tags to reader involves $O(K \log(N/K))$ physical-layer symbols.

2) Computational Complexity: The computation time of compressive sensing-based decoding performed at the back-end server turns out to be the major contributor to the overall computation overhead. In our implementation, we use the off-the-shelf CVX solver [2] to decode the aggregated responses and identify the missing tags, which involves computation time of $O(N^3)$. As our scheme needs the access to physical-layer information, we implement our scheme using software radios. Physical-layer symbols are collected using the software radios and transferred to PC via Ethernet links. Our implementation using commodity PCs can easily cope with the computation tasks in subsecond time with thousands of tags. In P-MTI, both RFID reader and RFID tag only perform lightweight routine computation tasks, and the computational overhead is negligible. We note that our scheme needs the slight extensions to EPCglobal Gen-2 protocol, e.g., a new command for missing tag identification and the convex optimization-based decoder at the reader, etc.

3) Divide and Conquer: Due to the constraints of antenna sensitivity, the measurement error of RFID reader would increase when a large number of tags concurrently respond. Moreover, the computation time increases with the number of tags. As the RFID reader knows the number of tags, the RFID reader can adaptively divide the tags into several smaller subsets when necessary. For instance, by querying the tags with a particular p-bit prefix, the tags can be divided into 2^p subsets with fewer tags in each subset using the `Select` primitive operation of the EPCglobal Gen-2 standard. The RFID reader may monitor the mutually exclusive subsets iteratively and combine the results.

4) Channel Dynamics: In practice, wireless channels change over time. P-MTI naturally embraces the channel dynamics. First, the compressive sensing-based signal reconstruction is robust to channel noise. P-MTI takes measurement noise (due to channel dynamics, interference, quantization, etc.) into consideration and enhances its robustness based on the theory of stable recovery (Section III-D). Second, the detection function $f(z_{\Delta i})$ obviates the need of accurate channel measurements. In stationary environment settings (e.g., medicine store, military basis, etc.), the channel variation is small. If channel condition changes dramatically during a short period, P-MTI may draw a false detection result. One possible solution is to do extra measurements to ensure the detection results. For instance, the RFID reader may query the potential missing tags to respond immediately. If no response is sent back from the tag, then the reader can confidently conclude its absence. Tag mobility also introduces channel dynamics. While P-MTI primarily focuses on monitoring static goods (e.g., in inventory management), our scheme inherently tolerates low-mobility scenarios where the channel dynamics are within the stability range as discussed in Section III. Following the existing approaches [20], [31], we focus on the wireless channels without the intentional interference from adversaries. P-MTI may benefit from a wise channel selection (e.g., BLINK [40]) to ensure channel quality.

IV. Implementation

Although the EPCglobal Gen-2 standard specifies many operations of tags and readers, the practical implementation is left to the manufacturers' choices. Production RFID readers (e.g., Alien ALR 9900+ RFID reader [1]) only provide limited interfaces and do not expose physical-layer information to users. To explore the lower-layer information, we build a prototype missing tag identification system based on the USRP software defined radio and the programmable WISP tags. Fig. 4 shows the testbed. We implement a prototype software defined RFID reader using USRP N210 based on the GNURadio toolkit and Gen2 RFID project [5]. In particular, one USRP RFX900 daughterboard operating in the 900-MHz UHF band [4] is connected to the USRP N210 as the front end. We connect the daughterboard to Alien ALR-8696-C circular polarized antennas with 8.5 dBic antenna gain [1]. The antennas provide sufficient fidelity to detect minute variations of backscattered signals. The USRP N210 is connected via Gigabit Ethernet to a laptop equipped with one qual-core 2.67-GHz processor and 2.9 GB memory running Ubuntu 10.10. The source code for the USRP N210 RFID reader is available online [7].

Fig. 4. Testbed: Two circular antennas are mounted to USRP N210. The USRP N210 is connected via GigE to a laptop that acts as an RFID reader.

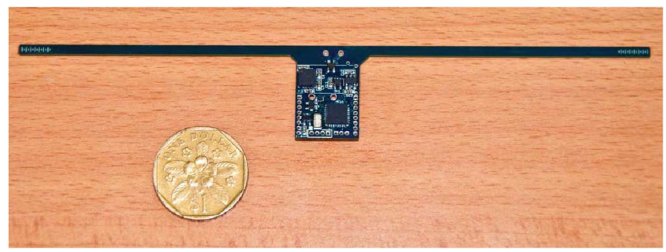

Fig. 5. WISP tag.

P-MTI requires each RFID tag to generate random bits with its ID as the seed. As current commodity passive tags (e.g., Alien ALN tags) do not expose flexible interface for programming, we prototype with the WISP programmable tags (Fig. 5). Each WISP tag mainly consists of an antenna circuitry and an ultra-low-power 16-bit MSP430 microcontroller. The circuitry is used to harvest energy from the radio frequency signals and backscatter the signals for communication. A capacitor stores the harvested transient energy and supplies power for computation and communication. The EPCglobal Gen-2 protocol [3] has been partially implemented in the WISP firmware, which has most of the necessary components to implement P-MTI. We extend the firmware to let the tags work in concert with the software defined reader to achieve the functionality of missing tag identification. The programming overhead is small, and the extension only requires slight updates to the EPCglobal Gen-2 standard. Constrained by transmission power of USRP with 200 mW and limited number of available WISP tags, currently we can only perform experiments in small-scale static settings. Yet, we believe P-MTI can be implemented in large-scale production RFID systems.

The EPCglobal Gen-2 standard specifies a set of routine operations (e.g., `Query`, `Write`, `Select`, `ACK`, etc.). We extend the EPCglobal Gen-2 following the conventional reader-initiated approach by adding the missing tag identification routine named `MTI`. `MTI` initiates the missing tag identification process. Fig. 6 plots the magnitude of received signals at RFID reader during the `MTI` process. The RFID reader initiates the monitoring by transmitting continuous waves to power up the tags. The reader then broadcasts the operation code of `MTI`. When receiving the `MTI` command, each tag sends the pseudo random bits using on–off keying as specified in P-MTI. The aggregated responses from tags are received and decoded at the reader. The reader terminates the monitoring by simply stopping the radio frequency waves.

A. Backscatter Signals

The differential of aggregated responses-based approach requires that the wireless channel remains relatively stable during consecutive measurements. We let three WISP tags transmit random bits and measure the received signal strength at the USRP reader in the office environment. Each tag transmits a packet of 32 symbols per second. The RFID reader measures the average signal strength of the 32 symbols. We conduct 40 measurements for each tag and show the strength of backscatter signals from three tags in Fig. 7. We find that the received backscatter signals remain quite stable during the measurements of 40 s. As shown in Fig. 2, the signal strength remains even more stable within the transmission of one packet.

B. Backscatter Synchronization

Passive RFID tags work on harvested energy from radio frequency signals of reader. As the interrogation environment varies, the energy harvest rate differs from tags to tags. Therefore, some tags may wake up earlier than other tags, which introduces response offsets. We set a conservative period of transmitting continuous waves to power the tags before broadcasting the `MTI` command. The tags transmit signals concurrently after receiving the `MTI` command. Ideally, the signals from multiple tags would arrive at the reader at the same time. Fig. 8 shows the CDF of offsets among seven WISP tags. According to our experiments on WISP RFID tags, the offsets are within 1.4 μs with the 90th percentile of 0.75 μs. When the data rate is 40 kb/s, a 1.4-μs offset counts for 5.6% of bit width (25 μs), which is sufficiently small for decoding. An independent work [31] reports similar synchronization accuracy on Moo RFID tags [39].

C. Identifying Missing WISP Tag

We prototype a missing tag identification system where a software defined RFID reader monitors five WISP tags. Fig. 9(a) depicts the received signals at the reader when all the five WISP tags are present in the first measurement instance. We intentionally take away one tag to emulate a missing tag event. Fig. 9(b) plots the received signals from the four remaining tags. Fig. 9(c) plots the differential of the two measurements and the signals when only the missing tag responds. We note that the magnitude of received signal strength is influenced by the wireless channel as well as the automatic gain control of RFID reader. We consider the influence of automatic gain control as a part of the wireless channel. Although the magnitude of received signal differs due to channel attenuation and gain control, we see that the differential exhibits similar patterns with the signals when only the missing tag responds. With the knowledge of the differential signals, we can accurately identify the missing tag by solving the convex optimization problem (7). For clarity, here we only present the instance when only one tag is missing. In the experiments when more than one tag is missing, we find that P-MTI can accurately identify them as well.

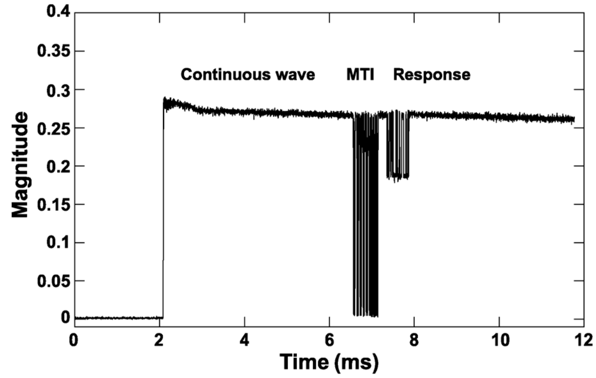

Fig. 6. MTI process.

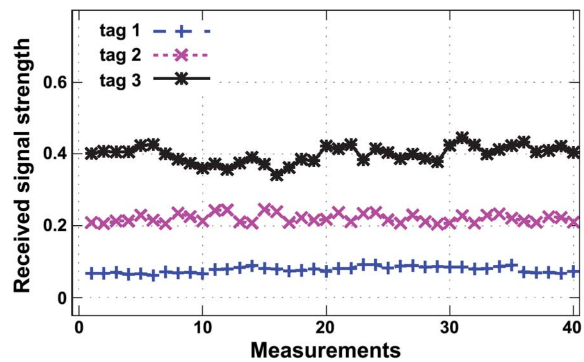

Fig. 7. Received signal strength.

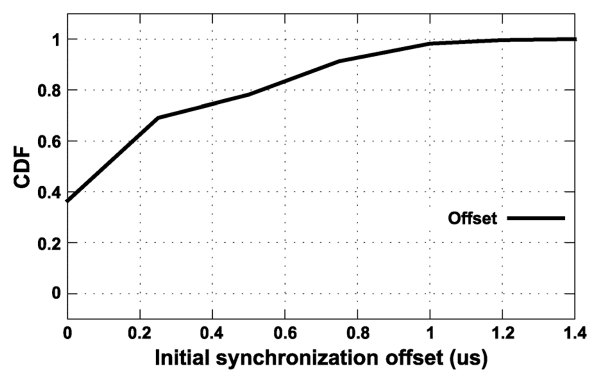

Fig. 8. Initial offsets among tags.

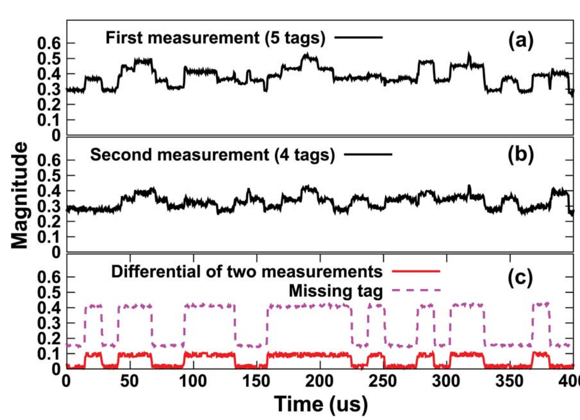

Fig. 9. Received signals at RFID reader: (a) aggregated signals from five tags; (b) aggregated signals from fourtags; (c) differential of the two measurements.

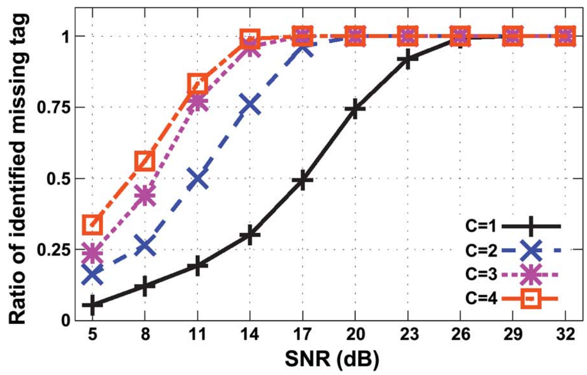

Fig. 10. Ratio of successfully identified missing tags across different channel conditions.

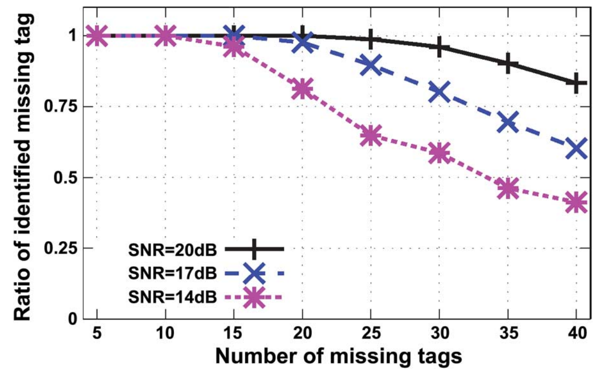

Fig. 11. Ratio of successfully identified missing tags with different number of missing tags.

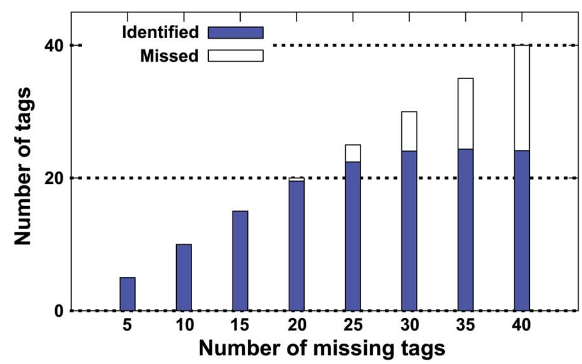

Fig. 12. Identified and missed tags with different number of missing tags, SNR $= 17$ dB, and $K_{\mathtt{Max}} = 20$.

V. Evaluation

In the following, we turn to large-scale simulations to evaluate our missing tag identification scheme. We first analyze the proposed P-MTI. We compare P-MTI with state-of-the-art protocols IIP [20] and Protocol-3 [38].

A. Simulation Setup and Performance Metrics

We build a custom simulator based on CVX solver [2] and run the simulations on MATLAB. For P-MTI, we study the various scenarios with different numbers of tags and readers and wireless channel conditions. For fair comparison, we adopt the same system parameters used in benchmark protocols [20], [38]. In particular, the transmission time of a short response is specified as $t_s = 0.8$ ms, and the transmission time of a 96-bit tag ID is specified as $t_{tag} = 2.4$ ms, which gives an approximate bit rate of 40 kb/s. We measure the communication time between RFID readers and tags, the initialization time, as well as the protocol execution time in the evaluation. All results are obtained by averaging over 100 runs if not specified otherwise.

B. P-MTI Investigation

Wireless communication is error-prone in practice, and thus whether P-MTI can accurately identify missing tags in the presence of channel noise is worth investigating. We simulate 1000 tags uniformly distributed in the coverage of each RFID reader, among which 20 tags are missing. We specify the number of measurements $M = CK_{\mathtt{Max}} \log(N)$, where $N = 1000$ and $K_{\mathtt{Max}} = 20$ with different C. We randomly select the missing tags for simulation. Fig. 10 plots the ratio of successfully identified missing tags to the total number of missing tags across different signal-to-noise ratios (SNRs). As expected, when SNR is very low, P-MTI cannot identify all the missing tags. With the SNR ≥ 17 dB and $C \geq 3$, P-MTI correctly identifies more than 98% of missing tags. P-MTI can further improve the identification accuracy with extra measurements (i.e., with larger C). In Fig. 10, the marginal accuracy improvement diminishes with the increased number of measurements. For instance, the accuracy with $C = 4$ is only slightly higher than that with $C = 3$. In practice, we set $C = 3$ to balance the accuracy and measurement overhead.

Another parameter that P-MTI needs to specify is the estimated maximum number of missing tags. The number of missing tags can sometimes exceed the estimated maximum number. We evaluate P-MTI with different numbers of missing tags with $K_{\mathtt{Max}} = 20$, under noisy channel conditions (i.e., SNR $= 14$, 17, and 20 dB). Fig. 11 plots the ratio of successfully identified missing tags to the total number of missing tags when the number of missing tags varies from 5 to 40. According to the results, when the number of missing tags is smaller than $K_{\mathtt{Max}}$ (i.e., <20), P-MTI can accurately identify the missing tags. When the number of missing tags exceeds $K_{\mathtt{Max}}$, P-MTI cannot identify all the missing tags. Therefore, the RFID reader needs to adjust $K_{\mathtt{Max}}$ to ensure that no more than $K_{\mathtt{Max}}$ tags would be missing. Fig. 12 plots in detail the missing tag identification results with different numbers of missing tags, SNR $= 17$ dB, and $K_{\mathtt{Max}} = 20$. Although P-MTI may fail to identify some tags when the number of missing tags exceeds $K_{\mathtt{Max}}$, the number of successfully identified missing tags would become very close to or even exceed $K_{\mathtt{Max}}$. When the number of missing tags exceeds 20, however, the number of successfully identified ones becomes larger than 20. In such cases, the reader can adaptively increase $K_{\mathtt{Max}}$ to ensure that $K_{\mathtt{Max}}$ is indeed larger than the number of missing ones. A larger $K_{\mathtt{Max}}$ can correct the error due to underestimation of missing tags at the cost of the increased communication overhead. We note that it remains challenging to set the optimal value of $K_{\mathtt{Max}}$. One may use the tag cardinality estimation schemes [18], [21], [28], [42], [44] to adapt $K_{\mathtt{Max}}$ when the number of missing tags exceeds $K_{\mathtt{Max}}$. We show in the following that even in the most

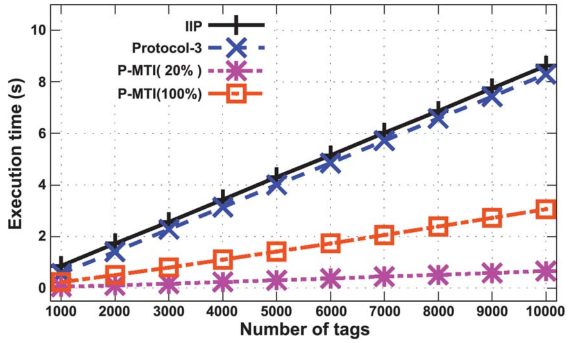

Fig. 13. Execution time comparison for the single-reader case.

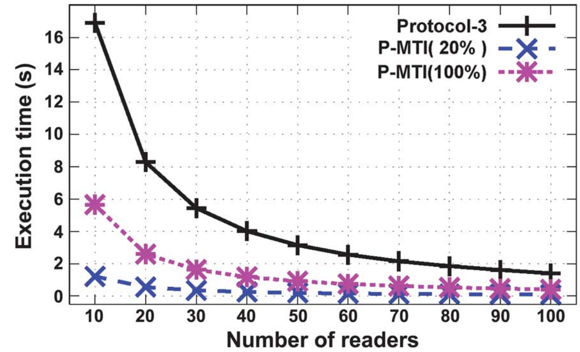

Fig. 14. Execution time comparison for the multiple-reader case.

TABLE I
ERROR RATES OF CLASSIFYING PRESENT TAGS AS MISSING

SNR	5dB	8dB	11dB	14dB	17dB	20dB
Error	0.42%	0.184%	0.034%	0.005%	0.0%	0.0%

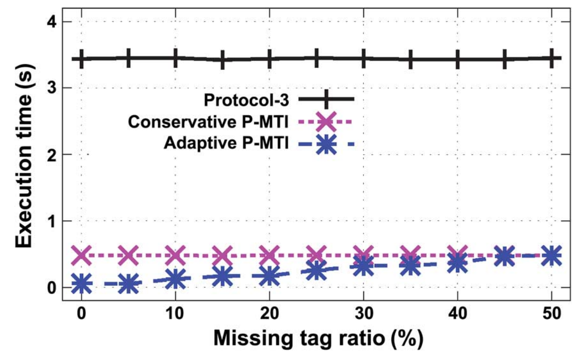

Fig. 15. Execution time comparison with the different missing tag ratio.

conservative setting (i.e., $K_{\texttt{Max}} = N$), P-MTI still achieves much higher processing efficiency compared to prior schemes.

We evaluate whether P-MTI would wrongly classify present tags as missing tags. In Table I, we measure the error rates of classifying present tags as missing tags across different SNRs. According to the experiment results, on average only 1.8 out of 980 (i.e., 0.184%) present tags are wrongly considered as missing tags when SNR $= 8$ dB. Generally, the error rates decrease as the SNR increases. In particular, no present tags are wrongly considered missing when SNR > 14 dB.

C. Performance Comparison

We compare P-MTI to the most recent protocols IIP [20] and Protocol-3 [38]. We adopt the same system parameters used in [20] and [38]. As IIP and Protocol-3 do not target at noisy channels, we do not simulate channel errors in the comparison study. For completeness, P-MTI however uses conservative parameter settings (e.g., $M = 3K_{\texttt{Max}} \log(N)$), which would favor the benchmark protocols. We investigate the transmission time of backscatter responses from tags to readers, the initialization overhead, as well as the protocol execution time in the evaluation. We note that the overall execution time is largely determined by the transmission time of backscatter responses from tags to readers, while the other communication overhead is very small (e.g., initialization time, reader-to-server transmission, etc.).

Single Reader: We note that Protocol-3 and P-MTI schedule multiple readers and achieve interrogation among nonoverlapping readers in parallel, while IIP views multiple readers as a single logical reader and does not benefit from parallel interrogation. Therefore, we first study the single reader case and compare IIP, Protocol-3, and P-MTI. Fig. 13 compares the overall execution time of IIP, Protocol-3, P-MTI (with $K_{\texttt{Max}} = 0.2N$), and P-MTI (with $K_{\texttt{Max}} = N$) with varied number of tags. According to the results, we find that P-MTI with conservative parameter settings of $K_{\texttt{Max}} = N$ can reduce the execution time by approximately 64% compared with IIP and Protocol-3. This performance gain stems from the efficient use of physical-layer information. With more realistic parameter settings of $K_{\texttt{Max}} = 0.2N$, P-MTI achieves even higher efficiency. The performance gain stems from the compressive sensing-based information reconstruction.

Multiple Readers: We compare the performance of P-MTI to Protocol-3 in the scenarios of multiple RFID readers. To study the scalability of different schemes, we simulate 50 000 tags with varied number of readers. We use the same RFID network topology for P-MTI and Protocol-3 and investigate the overall execution time. As shown in Fig. 14, with more readers, both P-MTI and Protocol-3 can effectively reduce the execution time by dividing the tags into smaller subsets and interrogating them in parallel. Nevertheless, the increased number of readers requires extra deployment costs. Thus, it is yet significant to further improve the communication efficiency. According to our experiment results, P-MTI can significantly reduce the execution time compared to Protocol-3, with/without the knowledge of missing tag ratio. In particular, P-MTI with conservative parameter setting only takes about 33% of the execution time of Protocol-3.

Number of Missing Tags: We compare the overall execution time of P-MTI to Protocol-3 with different ratios of missing tags. We simulate 50 000 tags in the coverage of 50 RFID readers. Fig. 15 plots the execution time with different missing tag ratios varied from 0% to 50%, which covers the typical missing tag events in practical applications. The adaptive P-MTI adaptively increases $K_{\texttt{Max}}$ when the number of missing tags becomes close to or exceeds $K_{\texttt{Max}}$. The conservative P-MTI conservatively sets $K_{\texttt{Max}} = 0.5N$. From Fig. 15, we find that the execution time of adaptive P-MTI increases linearly with the missing tag ratio, while the execution time of conservative P-MTI remains almost constant. We also find that the execution time of both adaptive and conservative P-MTI is much smaller than that of Protocol-3 across different missing tag ratios.

VI. Related Work

Many works study the problem of RFID identification that aims at identifying the tags through collision arbitration [27], [33]. The RFID identification protocols can be generally classified into two categories: Aloha-based [29] and tree-based [11] protocols. In Aloha-based identification protocols, each tag randomly selects a time-slot to transmit its ID. If a time-slot is selected by only one tag, then the tag can be successfully identified. If more than one tag selects a time-slot, then the tags cannot be identified due to tag–tag collisions. In tree-based identification protocols, the reader detects whether any tag–tag collision occurs and adaptively divides the tag set into small subsets until all tags are successfully identified. While the RFID identification protocols can be directly borrowed to address the missing tag identification problem, the collision arbitration overhead as well as the transmission overhead of tag IDs increase with the number of tags and render such approaches inefficient for monitoring large number of tags.

Many cardinality estimation protocols estimate the number of tags [18], [21], [22], [28], [42], [44], which may serve as primary inputs for missing tag identification. Such approaches, however, cannot be directly borrowed to achieve the item-level missing tag identification since they only provide a rough estimation of tag cardinality for large-scale RFID systems.

Tan *et al.* [30] present TRP, which detects the missing tag events when the number of missing tags exceeds a threshold. In EMD [24], each tag is sampled with a participation probability in each protocol execution and improves the time efficiency. MSMD [25] jointly considers energy and time efficiency and achieves substantial reduction in both energy cost and execution time.

Recent works study the problem of identifying the missing tags [38]. In [20], Li *et al.* propose a missing tag identification protocol that can detect the missing tag events with certainty and identify the missing ones. In [38], Zhang *et al.* significantly reduce the missing tag identification time by more efficiently scheduling and utilizing multiple readers. Unlike prior approaches that focus on upper-layer information, our approach effectively leverages the aggregated responses in the physical layer to improve the monitoring efficiency.

Many works study the problem of collecting data from computational RFID tags integrated with various sensors. Yue *et al.* [35] present a data collection approach using the Bloom filter. Flit [16] improves the throughput of data transmission through a bulk transmission. BLINK [40] improves the link-layer performance with link quality measurement, mobility prediction, and rate adaptation. HARMONY [45] enables CRFIDs to send large data packets to commodity readers. Fyhn *et al.* [15] propose to use the successive interference cancellation to iteratively reconstruct one signal at a time and then remove it from the received signal, which shows promising results in recovering physical-layer collisions. Buzz [31] presents an efficient and reliable data collection approach for RFID systems leveraging physical-layer information. Zanetti *et al.* [36] study the problem of classifying different RFID tags using the physical-layer fingerprints. Kumar *et al.* [19] study how to recover physical-layer interferences to efficiently identify RFID tags. Although targeting totally different problems, the common rationale behind those works and our approach is that careful cross-layer designs may significantly improve the performance of RFID systems.

VII. Conclusion

In this paper, we study the missing tag identification problem in large-scale RFID systems. We propose P-MTI to leverage physical-layer information and substantially improve monitoring efficiency. We further present several optimization techniques to improve the performance. P-MTI leverages the sparsity of missing tag events and reconstructs tag responses through compressive sensing. To validate its efficacy, we implement a prototype system and extend the EPCglobal Gen-2 standard based on the GNURadio/USRP and WISP platform. We do extensive evaluation of P-MTI with large-scale simulations. The results demonstrate that P-MTI substantially outperforms the state-of-the-art schemes.

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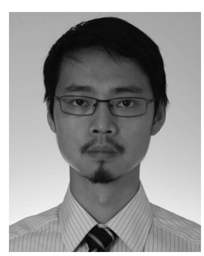
His research interests include RFID, distributed systems, and pervasive computing.



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