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

Yuanqing Zheng, Mo Li
School of Computer Engineering, Nanyang Technological University, Singapore
{yuanqing1, limo}@ntu.edu.sg

***Abstract*—RFID systems are emerging platforms that support a variety of pervasive applications. The problem of identifying missing tag in RFID systems has attracted wide attention due to its practical importance. This paper presents P-MTI: a Physical-layer Missing Tag Identification scheme which effectively makes use of the lower layer information and dramatically improves operational efficiency. Unlike conventional approaches, P-MTI looks into the aggregated responses instead of focusing on individual tag responses and extracts useful information from physical layer symbols. P-MTI leverages the sparsity of missing tag events and reconstructs tag responses through compressive sensing. We implement P-MTI and prototype the system based on the USRP software defined radio and Intel WISP platform which demonstrates the efficacy. We also evaluate the performance of P-MTI with extensive simulations and compare with previous approaches under various scenarios. The evaluation shows promising results of P-MTI in terms of identification accuracy, time efficiency, as well as robustness over noisy channels.**

I. Introduction

Radio Frequency Identification (RFID) systems are becoming important platforms that enable ultra-low power ubiquitous computing [18, 31]. RFID tags harvest energy from high power RF signals of a nearby RFID reader. A tag can switch the reflection coefficients of its antenna to backscatter or absorb the RF signals to send one-bit 0/1 information achieving ultra-low power communication. 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 [11, 33].

The problem of missing tag identification has attracted wide attention due to its practical importance [16, 28]. For example, RFID tags can be attached to items as labels in a warehouse, and RFID readers can monitor them for anti-theft purpose. Such a problem of item-level monitoring also appears in applications of healthcare, logistics, military, etc. When the number of tags is small, one may frequently identify all the tags and check if anyone is missing. When the number of tags scales up, tag-tag collisions become increasingly severe and render collision arbitration schemes highly inefficient.

Recently, many novel protocols have been proposed to detect the missing tag events. Typically, those approaches iterate over individual tag responses for identifying the missing tags. Due to the inherent nature of sequential look-up, conventional approaches consume a substantial number of time slots that is linearly proportional to the total number N of tags. Although many advances have been made, such approaches largely overlook the physical layer information and merely rely on upper layer information, rendering them less efficient for realtime 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 provides 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 simple on-off keying. In 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 non-zero 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, $\mathbf{x}_\triangle = \mathbf{x}_t - \mathbf{x}_{t-\triangle}$, where K non-zero entries in $\mathbf{x}_\triangle$ indicate the missing tags. As the differential of the two consecutive responses $\mathbf{y}_\triangle = \mathbf{A}\mathbf{x}_\triangle$, which can be formulated as a standard compressive sensing problem [12], we can efficiently recover $\mathbf{x}_\triangle$ with only a substantially smaller number of measurements.

We implement a prototype system and validate P-MTI design based on the Universal Software Radio Peripheral (USRP) software defined radio with the Intel Wireless Identification and Sensing Platform (WISP) programmable RFID tags. We also investigate our approach in large-scale settings with extensive simulations compared with existing approaches [16, 28]. The experiment results show that the proposed P-MTI scheme significantly improves the time efficiency. In particular, P-MTI can effectively reduce the transmission time by approximately 65% over state-of-the-art approaches. The improvement stems from both the efficient use of lower layer information and the compressive sensing based information 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 programmable tags.

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 backend 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 large number of tags rather than the backend server. We also study parallel interrogation of multiple readers [28].

In this paper, we exclusively focus on the RFID system operating in the 900MHz 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) according to the reader command. Due to the constraints of transmission power, the communication bandwidth is generally narrow and thus can be mathematically modeled using a single complex number [23]. Following existing works [16, 23, 28], we assume that the uplink communication from tags to readers is synchronized by the readers. As the uplink data rate is low, the synchronization among the tags can generally be achieved in practice [23]. Such a system model has been adopted in many RFID systems compliant with 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. Such an open framework motivates novel designs to meet practical needs 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 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 root case of such missing tag events is beyond the scope of this paper.

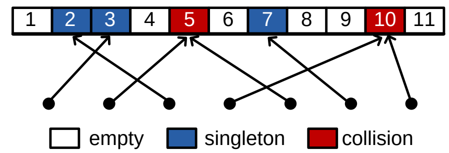

Fig. 1. Frame-slotted Aloha: 7 tags contend for 11 time slots.

B. Problem description

Consider an RFID system $\mathbf{N} = \{n_1, n_2, \dots, n_N\}$ 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 $N = |\mathbf{N}|$. In this paper, we particularly focus on the cases where $N \gg K \geq 0$. If most tags are missing and only a small number of tags are present, one may directly identify the present tags.

To ensure realtime 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 [16]. Generally, such schemes sequentially look up individual tag responses and only differentiate the empty/sington/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 the different types of slots.

To improve monitoring efficiency, in this work 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 slight updates to the protocol stack at tags without introducing extra computation or communication overhead.

III. P-MTI design

We first explain the rationale of P-MTI design (Section III-A). We present a basic solution which leverages the physical layer information for missing tag identification (Section III-B). We then explore the sparsity of missing tag events and use compressive sensing technique to enhance the missing tag identification efficiency (Section III-C). We combine several optimization methods to achieve higher overall performance (Section III-D and Section III-E). We finally discuss additional design considerations (Section III-F).

A. P-MTI rationale

The conventional schemes generally exploit the frame-slotted Aloha protocol to identify the missing tags [16, 28]. Figure 1 illustrates an instance where 7 tags contend for 11 time slots. Say that one tag should have responded in a singleton slot (e.g., the 7th time slot) if present, but no response is received from the time slot. Then the reader may infer that the tag is missing. In such schemes, less information can be extracted from empty and collision slots. As each tag

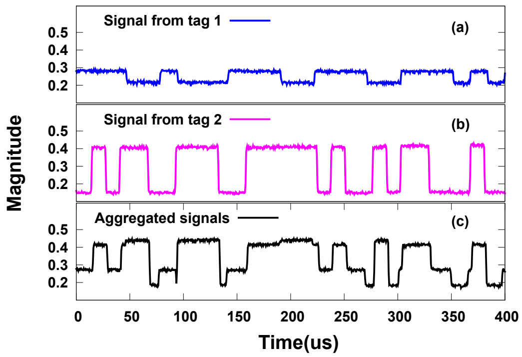

Fig. 2. Received signals at RFID reader: (a) Signals from tag 1; (b) Signals from tag 2; (c) Aggregated signals from the two tags.

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 [16]. Although many advances have been achieved in missing tag identification [16, 28], existing approaches largely overlook the PHY information and merely extract limited amount of information at 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]. Figure 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, Figure 2(b) depicts the signals from tag 2. The magnitude of received signal 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 (Figure 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 7 tags (i.e., tag 1 – 7), and we let them send random bits concurrently as in Figure 3. The responses from tags mix in the air and aggregate at the reader. The reader will receive physical layer symbols from all the 7 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

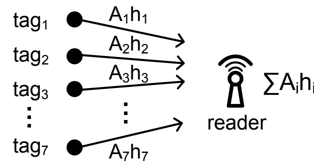

Fig. 3. Response signals from 7 tags mix in the air and aggregate at the reader. If tag i is missing, then its contribution to the aggregated physical layer symbols would be missing.

leverage the differences of physical layer symbols to detect and identify the missing tags. Departing from conventional schemes which 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 is 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 non-zero (zero) entries representing presence (absence) of tags. As the backscatter communication is generally within a narrow wireless band [23], 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 [23]. Therefore, we assume $\mathbf{H} = diag(h_1, h_2, \ldots, h_N)$, 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 $z_i = h_i x_i$ [23]. As $\mathbf{x}$ is binary vector, we have $z_i = h_i$ if $x_i = 1$, and $z_i = 0$ otherwise. Hence, Eq.(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 Eq.(2) with the knowledge of $\mathbf{y}$ and $\mathbf{A}$. The non-zero entry $z_i = h_i$ is the channel coefficient between tag i and the reader. A zero entry $z_j = h_j = 0$ 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 Eq.(2), we generally 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 time slot, which can further reduce 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 $t-\Delta$, $\mathbf{y}_\triangle = \mathbf{y}_t - \mathbf{y}_{t-\Delta}$, and infer the dynamics of the tags. According to Eq.(2), we have

$$\mathbf{y}_\triangle = \mathbf{y}_t - \mathbf{y}_{t-\Delta} = \mathbf{A}\mathbf{z}_t - \mathbf{A}\mathbf{z}_{t-\Delta}. \tag{3}$$

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

$$\mathbf{y}_\triangle = \mathbf{A}\mathbf{z}_\triangle. \tag{4}$$

Ideally, the zero entries in $\mathbf{z}_\triangle$ imply that corresponding tags are present, while the non-zero entries indicate that the tags are missing. 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., $N \gg K \geq 0$ [16, 28]. In other words, $\mathbf{z}_\triangle$ is K-sparse, meaning that there are at most K non-zero entries in $\mathbf{z}_\triangle$ [12]. According to the theory of compressive sensing, the K-sparse vector $\mathbf{z}_\triangle$ can be accurately recovered with only $M = O(K \log(N/K))$ measurements, by solving the following convex optimization problem [12].

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

where $\|\cdot\|_{\ell_p}$ denotes ℓ_p-norm, i.e., $\|\mathbf{x}\|_{\ell_p} \triangleq (\sum_{i=1}^{i=N} |x_i|^p)^{1/p}$. Intuitively, the objective function of minimizing $\|\mathbf{z}_\triangle\|_{\ell_1}$ incorporates the fact that $\mathbf{z}_\triangle$ 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 $\mathbf{z}_\triangle$. In our implementation, we use the CVX solver [2] based on the interior-point algorithm [7]. It has been reported that $M = 3K \sim 4K \ll N$ measurements suffice to recover the K-sparse vector [17]. 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 $\mathbf{z}_\triangle$. When the number of missing tags exceeds $K_{\mathtt{Max}}$, our approach can identify at least $K_{\mathtt{Max}}$ missing tags, which allows P-MTI to effectively 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. Besides, unlike existing schemes which 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 [8]. 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 [14]. In the following, we enhance P-MTI's robustness against noise based on the theory of stable recovery [9]. Incorporating the noise, Eq.(4) can be rewritten as follows.

$$\mathbf{y}_\triangle = \mathbf{A}\mathbf{z}_\triangle + e, \tag{6}$$

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.

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

where the magnitude e is bounded by ϵ, i.e., $\|e\|_{\ell_2} \leq \epsilon$. The theory of stable recovery [9] tells us that the solution $\hat{\mathbf{z}}_\triangle$ to the convex optimization problem (7) is a good approximation of $\mathbf{z}_\triangle$, and $\|\mathbf{z}_\triangle - \hat{\mathbf{z}}_\triangle\|_2 \leq c\epsilon$ where c denotes a small constant. In other words, a small error in $\mathbf{y}_\triangle$ only slightly influences reconstruction of $\mathbf{z}_\triangle$. In order to identify missing tags, P-MTI only needs to distinguish the zero and non-zero entries in $\mathbf{z}_\triangle$. The noise may disturb $\mathbf{z}_\triangle$ and render the zero entries in $\mathbf{z}_\triangle$ non-zero (yet remaining small), affacting 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 $f(z_{\triangle i})$ for tag i as follows.

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

If the magnitude of $z_{\triangle i}$ 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, fast tag mobility, dramatic environment dynamics, etc.), P-MTI is experimentally proven to be robust in reasonably good channel conditions (Section V) and stationary environment settings (Section IV).

E. Multiple readers

Multiple readers are normally deployed to ensure a full coverage of a large monitoring area [28] due to power constraints, interrogation environment, etc. For instance, current RFID readers can only power up the passive RFID tags within approximately 10m. We denote the number of RFID readers as L which is generally constrained by the deployment budget. 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. Besides, the RFID readers with non-overlapping coverage can interrogate tags in parallel without the reader-reader interference.

Recent works propose to efficiently schedule multiple RFID readers to improve the performance [28]. 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 non-overlapping 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 backend 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 handled by the backend server with powerful computation capability.

F. 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 *ms*. As the RFID readers are normally connected with backend server via high speed links, the communication cost between readers and backend server is also small compared with that of the backscatter communication. The backscatter communication from tags to reader involves the transmission time of $O(K \log(N/K))$ physical layer symbols.

2) Computational complexity: The computation time of compressive sensing based decoding performed at the backend 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 $O(N^3)$. Our implementation using commodity PCs can easily cope with the computation tasks in sub-second time with thousands of tags. In P-MTI, both RFID reader and RFID tag

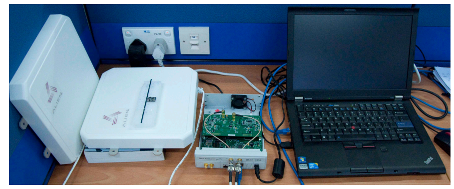

Fig. 4. Testbed: 2 circular antennas are mounted to USRP N210. The USRP N210 is connected via GigE to a laptop which acts as an RFID reader.

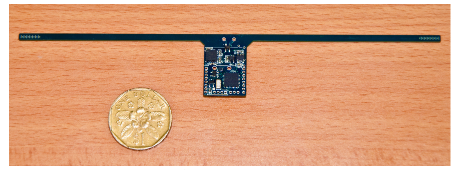

Fig. 5. A WISP tag.

only perform lightweight routine computation tasks required by the EPCglobal Gen-2 standard [3], and the computational overhead is negligible.

3) 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 enhance 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 focus 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 [16, 23], we focus on the wireless channels without the intentional interference from adversaries. P-MTI may benefit from a wise channel selection scheme (e.g., BLINK [30]) to ensure the channel quality as well.

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. Figure 4 shows the testbed. In particular, we implement a prototype software defined RFID reader using USRP N210 based on the GNURadio toolkit and Gen2 RFID project [5]. One USRP RFX900 daughterboard operating in the 900MHz

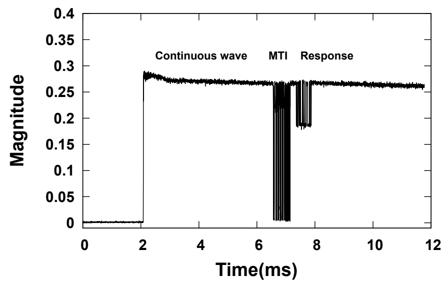

Fig. 6. `MTI` process. 1) the reader transmits continuous waves; 2) the reader broadcasts the `MTI` command; 3) When receiving `MTI`, each tag responds.

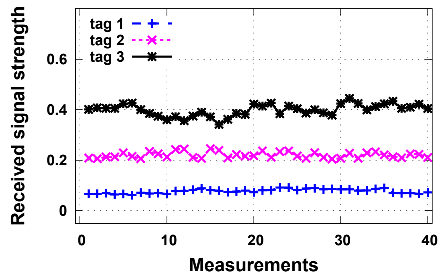

Fig. 7. Received signal strength from 3 tags.

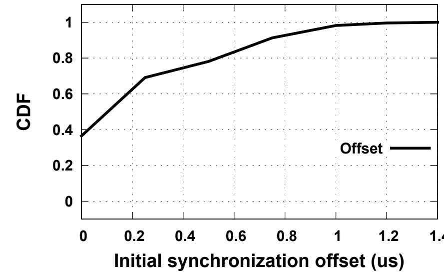

Fig. 8. Initial offsets among WISP tags.

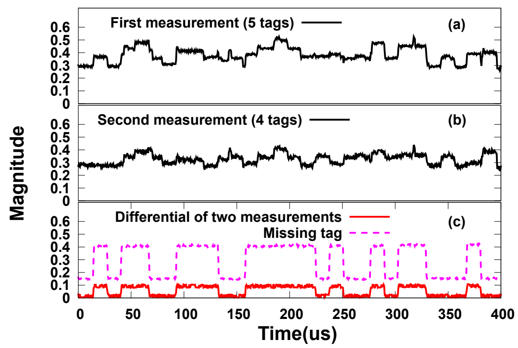

Fig. 9. Received signals at RFID reader: (a) Aggregated signals from 5 tags; (b) Aggregated signals from 4 tags; (c) Differential of the two measurements.

UHF band [4] is connected to the USRP N210 as the frontend. We connect the daughterboard to Alien ALR-8696-C circular polarized antennas with 8.5dBic antenna gain [1]. The USRP N210 is connected via Gigabit Ethernet to a laptop equipped with one qual-core 2.67GHz processor and 2.9GB memory running Ubuntu 10.10.

We implement RFID tags with the WISP programmable tags (Figure 5) based on the WISP4.1 hardware and firmware. 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 RFID 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 200mW 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 easily 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`. Figure 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 3 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 3 tags in Figure 7. We find that the received backscatter signals remain quite stable during the measurements of 40 seconds. As shown in Figure 2, the signal strength remains even more stable within the transmission of one packet which is much shorter.

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. In practice, however, the signals exhibit small offsets. Figure 8 shows the CDF of offsets among 7 WISP tags. According to our experiments on WISP RFID tags, the offsets are within $1.4\mu s$ with the 90th percentile of $0.75\mu s$. When the data rate is 40kbps, a $1.4\mu s$ offset counts for 5.6% of bit width ($25\mu s$) which is sufficiently small for decoding. A recent independent work [23] reports similar synchronization

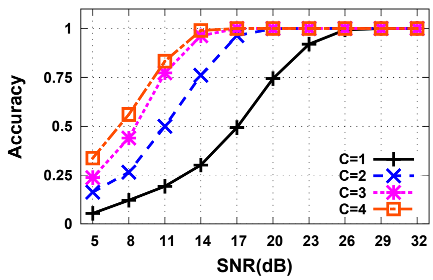

Fig. 10. Missing tag identification accuracy across different channel conditions.

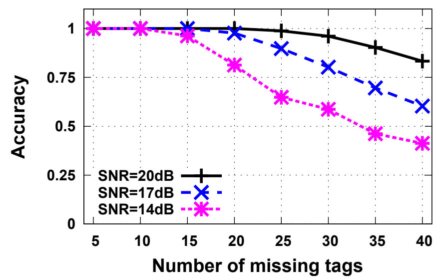

Fig. 11. Missing tag identification accuracy with different number of missing tags.

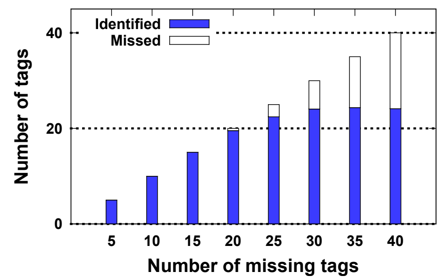

Fig. 12. Identified and missed tags with different number of missing tags, SNR=17dB, and $K_{\texttt{Max}}$=20.

accuracy on the Moo RFID tag [29] which is developed based on the WISP project.

C. Identifying missing WISP tag

We prototype a missing tag identification system where a software defined RFID reader monitors 5 WISP tags. Figure 9(a) depicts the received signals at the reader when all the 5 WISP tags are present in the first measurement instance. We intentionally take away one tag to emulate a missing tag event. Figure 9(b) plots the received signals from the 4 remaining tags. Figure 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 again control of RFID reader. 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 are missing, we find that P-MTI can accurately identify them as well.

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 then compare P-MTI with state-of-the-art protocols IIP [16] and Protocol-3 [28].

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 number of tags and readers and wireless channel conditions. For fair comparison, we adopt the same system parameters used in benchmark protocols [16, 28]. 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 bitrate of 40kbps. We focus on the communication time between RFID readers and tags, and ignore the negligible processing time on backend server. 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 $M = CK_{\texttt{Max}} \log(N)$, where $N = 1000$ and $K_{\texttt{Max}} = 20$ with different C. We randomly select the missing tags for simulation. Figure 10 plots the average accuracy of identifying the missing tags across different signal to noise ratio (SNR). As expected, when SNR is very low, P-MTI cannot always identify the missing tags. At moderate and high SNRs (e.g., 17-32dB), P-MTI achieves high accuracy. In particular, with the SNR≥17dB, the identification accuracies are consistently higher than 98% when $C \geq 3$. P-MTI can further improve the accuracy with extra measurements (i.e., with larger C) according to the application requirement. Generally, with more measurements P-MTI can achieve higher accuracy at the cost of extra communication and computation overhead in the presence of noise. According to Figure 10, we find that 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 $C = 3$. We thus set $C = 3$ to balance the accuracy and overhead in practice.

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 investigate identification accuracy of P-MTI with different number of missing tags which may exceed the estimated maximum number of $K_{\texttt{Max}}$=20, under noisy channel conditions (i.e., SNR=14, 17, and 20dB). Figure 11 plots the average accuracy of identifying the missing tags when the number of missing tags varies from 5 to 40. According to the results, we see that when the number of missing tags is smaller than $K_{\texttt{Max}}$ (i.e., $<$20), P-MTI can accurately identify the missing tags. When the number of missing tags exceeds $K_{\texttt{Max}}$, the accuracy decreases. Therefore, the RFID reader needs to adjust $K_{\texttt{Max}}$ to ensure that no more than $K_{\texttt{Max}}$ tags would be missing. Figure 12 plots in detail the missing tag identification results with different number of missing tags, SNR=17dB, and $K_{\texttt{Max}}$=20. Although P-MTI may fail to identify some tags

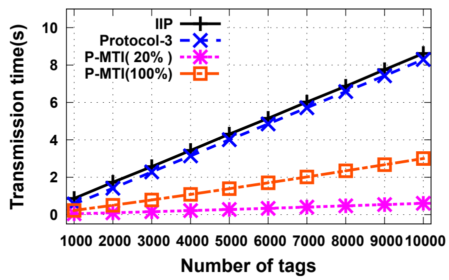

Fig. 13. Single reader case: Transmission time of IIP, Protocol-3, P-MTI ($K_{\text{Max}} = 0.2N$), and P-MTI ($K_{\text{Max}} = N$) with different number of tags.

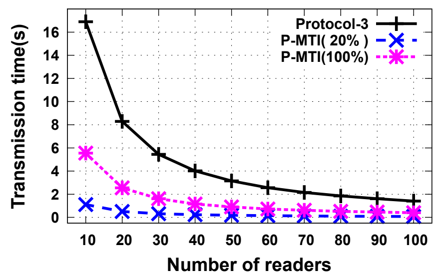

Fig. 14. Multiple reader case: Transmission time of Protocol-3, P-MTI ($K_{\text{Max}} = 0.2N$), and P-MTI ($K_{\text{Max}} = N$) with different number of readers.

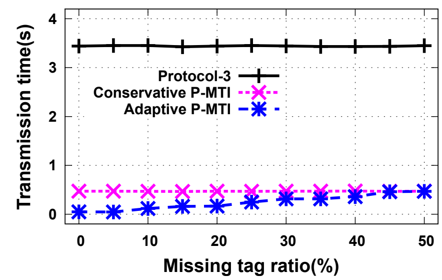

Fig. 15. Transmission time of Protocol-3 and P-MTI with/without a priori knowledge of missing tag ratio.

when the number of missing tags exceeds K_{Max}, the number of successfully identified missing tags would become very close to or even exceed K_{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_{Max} to ensure that K_{Max} is larger than the number of missing ones. A larger K_{Max} can correct the error due to underestimation of missing tags at the cost of the increased communication overhead. We show that even in the most conservative setting (i.e, $K_{\text{Max}} = N$), P-MTI still achieves much higher processing efficiency compared with existing protocols in the following.

C. Performance comparison

We compare P-MTI with the most recent protocols IIP [16] and Protocol-3 [28]. We adopt the same system parameters used in [16, 28]. 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., $M = 3K_{\text{Max}} \log(N)$) which would favor the benchmark protocols. As in IIP and Protocol-3, we mainly investigate the transmission time of backscatter responses from tags to readers, and ignore the negligible communication overhead (e.g., transmission time of initialization, reader to server transmission, etc).

Single reader. We note that Protocol-3 and P-MTI schedule multiple readers and achieve interrogation among non-overlapping 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. Figure 13 compares the transmission time of IIP, Protocol-3, P-MTI (with $K_{\text{Max}} = 0.2N$), and P-MTI (with $K_{\text{Max}} = N$). According to the results, we find that P-MTI with conservative parameter settings can reduce the transmission time by approximately 65% compared with IIP and Protocol-3. With more realistic parameter settings of $K_{\text{Max}} = 0.2N$, P-MTI achieves even higher efficiency. The performance gain of P-MTI stems from the efficient use of physical layer information and the compressive sensing based information reconstruction. With the knowledge of maximum number of missing tags, P-MTI can achieve higher efficiency rather than using the conservative parameter settings.

Multiple readers. We compare the performance of P-MTI with Protocol-3 in the scenarios of multiple RFID readers. 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 transmission time. As shown in Figure 14, with more readers both P-MTI and Protocol-3 can effectively reduce the overall transmission 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 transmission time compared with Protocol-3, with/without the knowledge of missing tag ratio. In particular, P-MTI with conservative parameter setting only takes about 33% of the transmission time of Protocol-3.

Number of missing tags. We compare the transmission time of P-MTI with Protocol-3 with different ratio of missing tags. We simulate 50,000 tags in the coverage of 50 RFID readers. Figure 15 plots the transmission 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_{Max} when the number of missing tags becomes close to or exceeds K_{Max}. The conservative P-MTI conservatively sets $K_{\text{Max}} = 0.5N$. From Figure 15, we find that the transmission time of adaptive P-MTI increases linearly with the missing tag ratio, while the transmission time of conservative P-MTI remains almost constant. We also find that the transmission 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 which aims at identifying the tags through collision arbitration [19, 24]. The RFID identification protocols can be generally classified into two categories: Aloha-based [21] and tree-based [10] 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 select 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 processing time increases with the number of tags and renders such approaches inefficient for monitoring large number of tags.

Many cardinality estimation protocols estimate the number of tags [15, 20, 32], which may serve as primary inputs for missing tag identification. Such approaches, however, cannot be directly borrowed to detect the missing tag events since they only provide a rough estimation of tag cardinality.

Recent works study the problem of tag monitoring and identify the missing tags [28]. In [22], Tan *et al.* present a missing tag monitoring protocol which can detect the missing tag events when the number of missing tags exceeds a user-defined threshold. In [16], Li *et al.* propose a missing tag identification protocol which can detect the missing tag events with certainty and identify the missing ones. Zhang *et al.* [28] significantly reduce the missing tag identification time by more efficiently scheduling and utilizing multiple readers. Unlike the existing approaches which 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.* [25] present a data collection approach using the Bloom filter. Flit [13] improves the throughput of data transmission through a bulk transmission. BLINK [30] improves the link layer performance with link quality measurement, mobility prediction, and rate adaptation for RFID communication. Buzz [23] presents an efficient and reliable data collection approach for RFID systems leveraging physical layer information. Zanetti *et al.* [26] study the problem of classifying different RFID tags using the physical layer fingerprints. Although targeting at 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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