A Fast Item Identification and Counting in Ultra-dense Beacon Networks

Pai Chet Ng[Υ], James She[Υ], Petros Spachos[†], Rong Ran[‡]
[Υ] School of Engineering, Hong Kong University of Science and Technology. Email: pcng@ust.hk
[†]School of Engineering, University of Guelph. Email: petros@uoguelph.ca
[‡]Dept. of Electrical and Computer Engineering, Ajou University. Email: sunnyran@ajou.ac.kr

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***Abstract*—While many technologies (e.g., RFID, QR code, etc.) have been developed for items identification, they fail to provide continuous monitoring for items in transit. This paper introduces a Bluetooth Low Energy (BLE) beacon-based system, which can be deployed easily with any off-the-shelf smartphone without modification on the existing infrastructures. However, it is an elusive challenge to achieve a fast item identification and counting involving massive items stacked up inside a confined space (e.g., a container), resulting in an ultra-dense beacon network (UDBN). To this end, we propose a novel beaconing solution capable of informing the receiver about their own presence as well as the presence of their neighboring beacons for identification purpose. Specifically, our proposed solution provides a well-designed yet innovative protocol data unit (PDU) which allows the beacon to encapsulate its neighboring information into its own advertising packet. A prototype consisting of 300 beacons is implemented to demonstrate the feasibility of our proposed solution for real-world applications. The extensive experiment confirm the superiority of our proposed solution in delivering a fast item identification and counting in UDBN.**

I. Introduction

Identifying a massive volume of items is of critical importance to keep track of the items' quantity and prevent item lost. Over the last few decades, many technologies have been exploited to provide fast items identification. Among them, RFID technology has achieved a significant breakthrough. By installing an inbound gateway equipped with RFID reader, all items attached with an RFID tag can be identified immediately upon passing through. Moreover, the worker can use the RFID scanner to re-count the items from time to time to ensure the items' quantity. Many solutions [1] [2] have been proposed to enhance the items identification and counting with RFID. While such a prevailing RFID system (i.e., the inbound and outbound gateway, periodic scanning, etc) is able to monitor the items flow within a fix location (e.g., warehouse), item lost is still a serious issue encountered by many industries.

In fact, many items were reported lost during the transit period. Fig. 1 provides two real-world examples illustrating the items in transit. According to the recent reports from FBI [3], in transit items theft has caused a total of $15 to $30 billion dollars lost each year in the United States. This clearly indicates the current limitation of the large-scale RFID system for monitoring the items in transit. Consider the warehouse as an example, the items would be recorded during the loading time through the outbound gateway, and inspected during the unloading time when they reach the destination. Yet, the items

Fig. 1. Items lost always occur during the transit period, for example (a) transporting the baggages from airplane's compartment to the reclaim hall, or (b) transshipping the cargo from the port to distribution center.

are left unmonitored during the transportation! While there are a few technologies (e.g., GPS tracking) to track the truck, ship or airplane [4] [5], there exists no technology to monitor the massive items carried by these moving vehicles.

Recognizing this limitation, this paper presents a Bluetooth Low Energy (BLE) beacon-based system to bridge the gap in monitoring the items in transit. Specifically, the beacon-based system allows batch identification, which can uniquely identify many items at the same time, and keep track of the items' quantity by inspecting the list of identified items. Moreover, by integrating the beacon-based system with the existing RFID system, we can seamlessly transfer the monitoring task from RFID to beacon-based system when the items need to be transported out of the warehouse. For example, a BLE beacon can be attached to the items loaded through the outbound gateway, the information recorded by the gateway can be shared with the smartphone through the same backbone network connecting the RFID and the beacon-based system.

While BLE beacon has been widely adopted for many applications, for example, proximity detection [6] [7], smart building [8] [9], indoor localization [10] [11], smart interaction [12] [13], smart parking [14] [15] etc, so far, there is no application developed for the above purpose. In fact, fast and scalability are the two main concerns that prevent the adoption of beacon technology for batch identification involving massive items stacked up inside a confined space (e.g., shipping container), resulting in an ultra-dense beacon network (UDBN). Since the underlying technology of BLE beacon is totally different from RFID, existing RFID-based solutions could not be applied directly without first exploring the possible challenges associated with the beacon-based system. This paper provides a comprehensive overview of the beacon-based system and highlights the corresponding challenges.

Motivated by the challenges, this paper proposes a novel beacon protocol, namely peer beacon (pBeacon), that enables the beacon to periodically informing the receiver about their presence as well as the presence of their neighboring beacons for identification purpose. The intuition behind pBeacon is that even though some beacons might fail to reach to the receiver, they can still convey their information through their neighboring beacons. To achieve this purpose, pBeacon strategically encapsulates the neighboring information into its own advertising packet based on a novel protocol data unit (PDU) operating through a dual-mode beacon, which is able to broadcast and scan concurrently. Such a dual-mode operation is essential for the beacon to listen to their neighbors, updating its advertising packet, and advertise its packet such that the receiver can identify the beacon and its neighbors by inspecting the advertising packet.

To the best of our knowledge, this is the very first work that provides batch identification for items in transit with a novel solution which strategically addresses the challenges imposed by the UDBN. The main contributions of this paper are summarized as follows:

- pBeacon is an innovative yet well-design PDU operating through a dual-mode beacon to format the length constraint advertising packet such that the advertising packet can contain the identifiers of the neighboring beacons.
- we prototype our pBeacon solution into 300 existing BLE beacon devices. Extensive experiments were conducted to demonstrate the feasibility of pBeacon for real-world asset counting problem.
- our pBeacon protocol is compatible with any existing BLE devices. Hence, it is a cost-effective solution in which we can just implement our protocol directly to the existing device by performing the firmware update.

The rest of the paper is organized as follows. Section II reviews the development of BLE beacons and the related issue in network density. Section III introduces the system model and its associated challenges. Section IV presents our proposed solution. Section V provides a practical experiment with our prototype to evaluate the performance or our proposed solution. Section VI concludes the paper with future works.

II. Related Works

This section reviews the current research related to BLE beacon technology and the associated density issue.

A. BLE Beacon

BLE beacon is a promising technology, which has attracted a lot of interests lately thanks to the active involvement from Apple and Google. Beacon is an active transmitter which broadcast its advertising packet periodically [16]. The advertising packet is a length constraint packet formatted according to the PDU. There are two very popular PDUs: iBeacon from Apple [17] and Eddystone from Google [18]. iBeacon allocates $2\,bytes$ major and $2\,bytes$ minor as the identifier, whereas Eddystone allocates at least $20\,bytes$ for their Eddystone frame. Generally, these two PDUs only allow the beacon to broadcast their own information. This information is generally useful for promoting proximity-based marketing [19] or triggering proximity-based interaction [20]. Besides that, [10] leverages the received signal strength (RSS) of the packet for indoor localization with $19\,beacon/m^2$ and concluded that $1\,beacon/30m^2$ constitutes a dense beacon network.

B. The Density of Beacon Network

The density issue associated with beacon networks has been studied by [21] and [22]. In particular, [21] describes the density based on the placement of beacons according to a certain topology, and claimed that $0.5m$ is the maximum spacing between each beacon; whereas [22] considers the effect of additional scan response which congested the advertising channels. However, neither [21] nor [22] provide a comprehensive model to describe the network density from the receiver's perspective. The experimental conducted by [22] only consists of 20 beacons; whereas [21] only provides simulation result with up to 121 beacons distributed over a $100m^2$ area. In this paper, we first provide an experiment with 300 beacons and further extend the experiment with extensive simulation with 10 to 5000 beacons. Note that this is the first work that uses more than 100 real beacons to confirm the preciseness of our formulation before proceeding with extensive simulation.

III. System Model and Analysis

This section provides a description about the beacon-based system and analyzes the factors affecting the packet reception empirically. Note that we use beacon and item interchangeably to refer to the items attached with a beacon.

A. Beacon-based System

The beacon-based system consists of three subsystems: a beacon, the advertising channels and a receiver connecting to the cloud server, as shown in Fig. 2. The system can be developed with any Bluetooth-compatible receiver (e.g., smartphone) to interact with the low-cost BLE beacon directly without any modification on the existing hardware infrastructures. The cloud server is mainly used to facilitate the information exchange between different systems (e.g., RFID to beacon-based system and vice-versa) as well as coordinate the identification process. Each item attached with a beacon can communicate its presence to the receiver through the advertising packet, which is broadcast periodically according to a pre-defiend advertising interval T_a [23]. Three channels are allocated by the Bluetooth standard for the advertising purposes. Upon receiving the advertising packet, the receiver can decode the packet to retrieve the relevant information. The compositions of at least one beacon and a receiver form a beacon network.

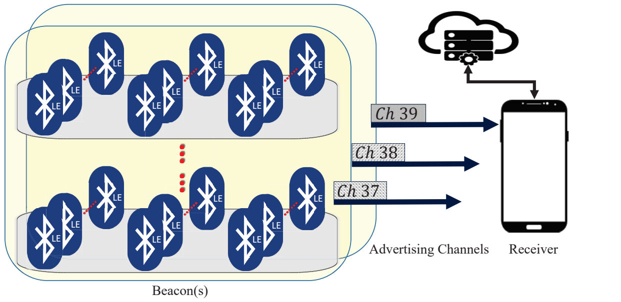

Fig. 2. The system model consists of (a) at least a beacon, (b) the advertising channels and (c) a receiver connecting to a cloud server.

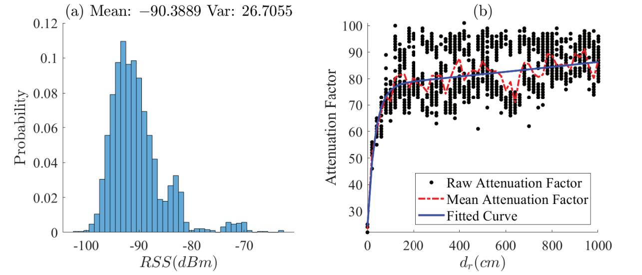

Fig. 3. By measuring the channel at the varying distances, we obtain: (a) the distribution of the noise power, and (b) the attenuation factor of the packet's RSS along the propagation path.

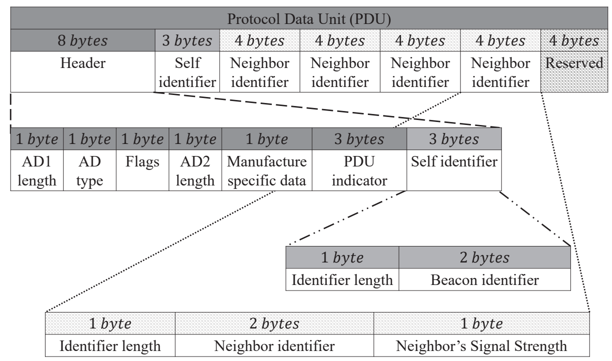

Fig. 4. pBeacon provides a well-designed yet innovative PDU to strategically encapsulate the information from neighboring beacons into the length constraint advertising packet.

Note that a group of beacons by themselves in the absence of a receiver could not be considered as a network. Having said that, the network density is computed based on the number of beacons within the reachable range from the receiver d_R. According to the BLE chipset datasheet, the theoretical range for a beacon operated at $0\,dBm$ is at least $10m$ (Further analysis is provided in Section III-B to verify the theoretical range). Based on this theoretical range, we argue that any beacon with distance less than $10m$ from the receiver is considered to be within the reachable range, i.e., $d_R = 10m$. Let $\mathcal{B} = \{1, 2, ..., b_i, ..., n\}$ be a set consisting of all the items attached with a beacon and $\mathcal{G}$ a set consisting of the beacons within d_R, the corresponding network density can be computed as follows:

$$D = \frac{u}{2\pi d_R^2}, \quad (beacons/m^2) \tag{1}$$

where $u = |\mathcal{G}|$ is the size of UDBN.

B. Empirical Analysis

Let d_r be the distance between the receiver and the beacon and P_r the RSS of the advertising packet measured by the receiver, we conducted an experiment by varying d_r from $0cm$ up to $4000cm$. The distribution of the noise power P_n measured by the receiver across all d_r is indicated in Fig 3(a). We can see that P_n varies from $-110dBm$ up to $-63dBm$ with $\mu_n = -90.39dBm$. The experiment confirms that the receiver can correctly decode the packet at least 99% of the time when P_r is above the noise floor. When P_r is below the noise floor, the receiver might still able to decode the packet correctly, but the chances are low.

As discussed, the maximum transmitting range of a beacon is about $10m$ when $P_T = 0dBm$ [23]. From the experiment, we observed that P_r is generally higher than the noise floor when the $d_r \leq 1000cm$. When $d_r > 1000cm$, P_r is subject to severe fluctuation. There are, still RSS fluctuations, for $d_r \leq 1000cm$, however, such fluctuations are less dominating if compared to the attenuation factor κ along its propagation path. When all these n beacons are scattered around d_R, D increases and causes more collisions between the beacons. In this case, the receiver might need a much longer time to identify all the beacons. Furthermore, if $d_r > d_R$, the chances for the advertising packet to reach to the receiver is extremely low. These, undoubtedly, create two open questions: 1) how to still identify those beacons fall outside d_R, and 2) can the system scales when n increases? In the next section, we provide our novel solution which can achieve fast identification despite $d_r > d_R$ and very large n.

IV. Our Proposed Peer Beacon (pBeacon)

Our pBeacon exploits a dual-mode beacon to operate as a broadcaster and scanner concurrently. Such concurrent operations are essential to enable the beacon to advertise their own packet at the same time listen to the packet from their neighboring neighbor. Note that the maximum packet length is only up to $31\,bytes$. For this reason, a PDU is proposed to strategically encapsulate the neighboring information into the advertising packet without compromising their own information. This section first presents our proposed pBeacon, before describing the identification process at the receiving end.

A. The Major Elements of pBeacon

BLE beacon is initially designed to work as a broadcaster using either iBeacon [18] or Eddystone [17] PDU to define the advertising packet [24]. The broadcaster mode allows the beacon to speak but not listening from its neighboring beacons. Furthermore, the length constraint packet might insufficient for the beacon to incorporate the information from the neighboring beacons. Recognizing these limitations, pBeacon designs a novel PDU to strategically format the advertising packet, and exploits a dual-mode beacon to concurrently working as a broadcaster and a scanner.

*1) **The Advertising Packet:*** The proposed PDU only use up to $27\,bytes$, as depicted in Fig. 4. The last $4\,bytes$ are reserved for future work, for example, implement an error checksum to increase the success rate of packet decoding. Note that the first $3\,bytes$ in the header is mandatory to define the Generic Access Profile (GAP) according to the BLE standard. All beacon has an AD type equal to 0x01 which indicates the flags used by the BLE device's physical channel [23]. Our proposed PDU set the flag to 0x06 which indicates the device is operated in an "LE General Discoverable Mode". The last $5\,bytes$ in the header is used to indicate the length of the rest of the data packet, the manufacturer specific data and PDU indicator. The PDU indicator is important in differentiating our proposed PDU from other PDUs.

The next $19\,bytes$ following the header are the useful information, which allows the receiver to identify the beacon(s). In particular, the first $3\,bytes$ carries the identifier of the beacon itself, and the subsequent $4\,bytes$ are used to indicate the neighboring beacons. Note that $2\,bytes$ are allocated to the beacon identifier, which means the system can accommodate up to a total of $2^8 \times 2^8 = 65,536$ different beacons at the same time. The last byte is used to indicate the signal strength of the neighboring beacon. This signal strength measured by the beacon is useful for future extension, for example, visualizing the spatial relationship between each node, or understanding the strength of the link connecting both nodes.

*2) **Dual-mode beacon:*** pBeacon enables the broadcasting and scanning operations concurrently without adding any extra chipset or applying any switching mechanism. Instead, we exploit the opportunity in the firmware design to enable such concurrent operations. Specifically, the scanning and broadcasting are two independent subroutines. By associating the broadcasting interrupt flag with the highest priority, the beacon will always execute the advertising event when its interrupt flag is triggered, even the beacon is in the midst of scanning. Note that the probability of triggering these two interrupt flags at the same time is extremely low due to the inherent priority design.

Let $\mathcal{R}$, $\mathcal{U}$ and $\mathcal{L}$ be a set denoting the list of beacon's identifiers received from neighboring beacons at time t, the list of uniquely identified beacons, and the list of beacons which is not yet in the uniquely identified list, the corresponding *Scan, Sort and Advertise* procedures for ith beacon is presented in Algorithm 1. The advertising packet is updated by inspecting $\mathcal{R}$, $\mathcal{U}$ and $\mathcal{L}$. If no new neighbor is observed at time t, the beacon will simple update its advertising packet $a_i(t)$ with the top 4 neighboring beacons from set $\mathcal{U}$.

Algorithm 1: Scan, Sort and Advertise by pBeacon

Input : $\mathcal{R} = \{a_b(t, byte(9:10)) : \forall b \in \mathcal{B} \wedge b \neq i\}$
Output: Advertising packet, $a_i(t)$

while t **do**
  if $\mathcal{L} = \mathcal{R} \setminus \mathcal{U} \neq \emptyset$ **then**
    if $|\mathcal{L}| \leq 4$ **then**
      $a_i(t) \leftarrow FormatAdv(\mathcal{L})$
    else if $|\mathcal{L}| > 4$ **then**
      sort: $|\mathcal{L}|$ according to their RSS
      $a_i(t) \leftarrow FormatAdv(\mathcal{L}(1:4))$
  $\mathcal{U} = \mathcal{U} + \mathcal{L}$
  else
    sort: $|\mathcal{U}|$ according to their RSS
    $a_i(t) \leftarrow FormatAdv(\mathcal{U}(1:4))$
    clear: $|\mathcal{U}|$
  if $t\%T_a == 0$ **then**
    Update: $a_i(t)$
  end
  Advertise: $a_i(t)$
end

Function *FormatAdv($\mathcal{L}$)***:**
  $j = 0$
  for $j < |\mathcal{L}|$ **do**
    $a_i(t, byte((12:13) + (j \times 4))) \leftarrow \mathcal{L}$
    increase j by 1
  end
  return $a_i(t)$
end

B. Batch Identification

Upon receiving the advertising packet, the receiver has to parse the packet in order to retrieve the identifier for identification purpose. Being able to uniquely identify the beacon is important to avoid redundant counting. A redundant count can lead to adverse effect which creates an illusion that the quantity of items is well-monitored even though some of the items are gone. In this paper, we provide a direct mapping method by first inspecting the PDU indicator in the header, and then use the known access key to retrieve the identifier of the beacon and its neighboring beacons. The ultimate goal of this work isto demonstrate a fast item identification and counting, in which designing a private encrypted key is not the core focus of this paper. However, we believe that it could be one of the possible direction for future works.

Let $\mathcal{R}$ be a set denoting the list of beacon's identifiers retrieved from the advertising packet $a_i(t)$, then the list of beacons identified by the receiver $\tilde{\mathcal{B}}$ after time t can be obtained with Algorithm 2. Specifically, an access key $K(\cdot)$ is used to map the packet with our proposed PDU, and I_{PDU} is the indicator denoting the type of the PDU. It is assumed that the system has a prior knowledge about the exact beacon list $\mathcal{B}$. Such an information can be easily obtained from the server, take the cargo for example, the total items loaded to the container can be passed directly from the RFID system to our beacon-based system, and vice-versa.

V. Implementation and Validation

The purpose of the practical implementation, besides demonstrating the feasibility of pBeacon for real-world applications, is to validate our formulation described in Section III before proceeding with extensive simulation. Section V-A first

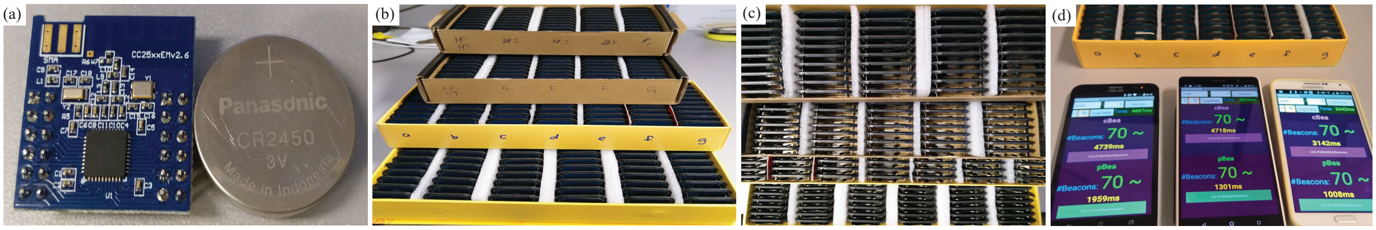

Fig. 5. Our prototype consists of at least 300 beacons, in which (a) the size of our dual-mode beacon is approximately the size of a coin-cell battery. These beacons were stacked up inside the boxes: (b) the side view, and (c) the top view. (d) Three smartphones were used during the experiment.

Algorithm 2: Batch Identification by the receiver

Input : Received packet: $a_i(t)$
Output: $\tilde{\mathcal{B}}$ and $\hat{n}$

if $n \neq \hat{n}$ **then**
  if $K(a_i(t, byte(5:7)))\%I_{PDU} == 0$ **then**
    $\mathcal{R} \leftarrow a_i(t, byte(9:10))$
    $b = 0$
    for $b + 14 < a_i(t, byte(3))$ **do**
      $\mathcal{R} \leftarrow a_i(t, byte(12+b:13+b))$
      increase b by 4
    end
if $\mathcal{L} = \mathcal{R} \setminus \tilde{\mathcal{B}} \neq \emptyset$ **then**
  $\tilde{\mathcal{B}} = \tilde{\mathcal{B}} + \mathcal{L}$
  $\hat{n} = |\tilde{\mathcal{B}}|$

TABLE I
THE DEVICES USED TO LOG THE DATA

Logged Data	Smartphone Model	API Level	BLE
1. Scan Event 2. Beacon ID 3. Beacon PDU	Samsung Galaxy Note 3	5.0 (Lollipop)	4.0
4. Beacon RSS 5. Local runtime 6. Global time	ASUS ZenFone 3	7.0 (Nougat)	4.2
7. Mac Address 8. Device Name 9. Battery	Nokia 7 plus	8.1 (Orea)	5.0

describes our proof-of-concept prototype, and then presents the the experimental results and validation in Section V-B.

A. Prototype

Our proof-of-concept prototype consists of over 300 beacons, an Android-based smartphone and a cloud server. During the development phase, we used the SmartRF Evaluation Board provided by Texas Instrument to program, deploy and debug pBeacon firmware into the CC2541 chipset to enabling the dual-mode beacon. The CC2541 chipset is a coin cell device from Texas Instrument, as shown in Fig. 5(a). The Android-based smartphone is installed with our *batch identification* App to work as a receiver. The App is written in C# using Xamarin Android Framework. An cloud server based on the open-source Apache framework is established to facilitate the identification process.

Upon validating the functionalities of our prototype, we then proceed with a massive implementation by flashing the firmware to over 300 beacons. Note that we only use 300 beacons for the experiment, the remaining are keep as a backup. These 300 beacons were packed into a few different. Fig. 5(b) and (c) show the side and top view of our experimental setup. The reason to pack the beacons inside a box is to emulate the scenario of those items loaded into a large container. In fact, our emulated scenario indicates a near worst-case scenario where the item's size is approximately the size of a beacon. However, in reality, the items to be loaded into a container can be at least quadruple larger than our beacon. Furthermore, we also use three different smartphones from different manufacturers with different API levels, as shown in Fig. 5(d), to demonstrate that our proposed solution is applicable for a wide range of devices. The smartphone models and also the data logged during the experiments are summarized in Table I. The experiment was performed by increasing n from 10 to 300, with 10 increment each step. Each experiment were repeated for at least 33 times, resulting in a total of $3 \times 33 \times 30 = 2970$ data, in which each data consists of all the 9 items listed in Table I.

B. Experiment and Validation

The results achieved by pBeacon for n from 10 to 300 are shown in Fig. 6. In particular, Fig. 6(a) indicates the total times required to identify all the n beacons. It is clear that pBeacon outperforms the baseline, and achieves a substantial performance gain when n increases. At least 50% time reduction is reported when $n = 300$. Moreover, the average performance of pBeacon (the black solid line) is still better than the best performance achieved by the baseline. Fig. 6(b), (c) and (d) show the number of beacons which can be identified within $1s$, $5s$ and $10s$, respectively. Clearly, pBeacon is able to identify all n beacons in $1s$ when $n < 100$, which is aligned with the result obtained in Fig. 6(a). When n increases, the baseline approach experiences a severe performance degradation, however, pBeacon still can still guarantee its performance with high $\hat{n}$. This implies that pBeacon can quickly identify a large number of beacons in a first few seconds when n is large. Such a big gain in the first few seconds allows pBeacon to achieve $\hat{n} \approx n$ as time increases, as illustrated in Fig. 6(c) and (d).

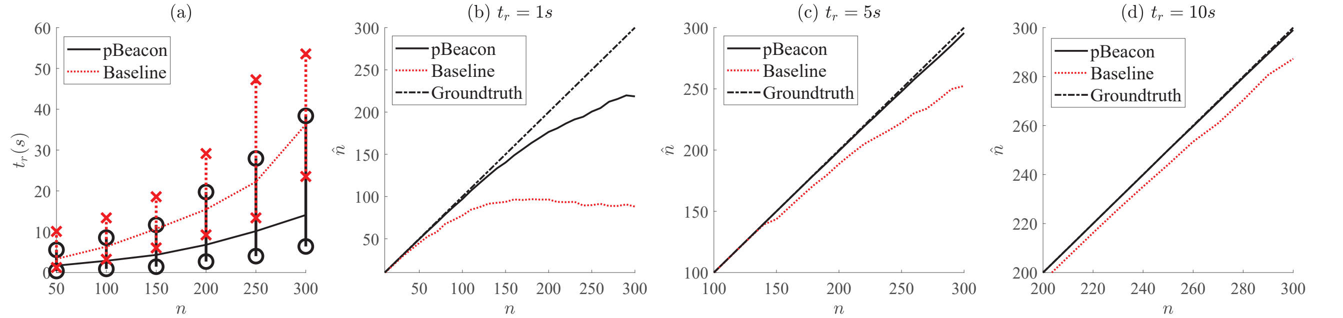

Fig. 6. The experimental results indicate: (a) the total time requires to identify $\hat{n} = n$ beacons; the $\hat{n}$ beacons which has been identified in (b) $1s$, (c) $5s$ and (d) $10s$, given n. Note that (c) zooms in to 100 to 300 beacons, whereas (d) zooms in to 200 to 300 beacons.

VI. Conclusions

The contributions of pBeacon are two-fold: 1) it exploits the opportunity in firmware design to enable a concurrent dual-mode operation such that the beacon can broadcast and scan at the same time; 2) it provides a well-designed PDU to strategically encapsulate the neighboring information into its constraint-length advertising packet. Experimental results indicate the superiority of pBeacon in providing a fast item identification and counting for massive items in transit. Throughout the paper, we also highlighted the possible future research directions, including 1) visualizing the spatial relationship between each beacon using the RSS information encapsulated in the advertising packet, 2) investigating the trade-off between the network density and the advertising interval on the system performance, and 3) designing a secure key for parsing the advertising packet. In our future work, a large-scale field test involving thousands of cargo would be carried out as an initial effort in presenting our proposed pBeacon for real-world deployment.

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