Postprint: Large-Scale RFID Tag Inventory Methods in the Internet of Things

Authors: Chen Yihong, Wang Jin, He Chunlin, He Jialin

Date: 2018-05-20T00:00:00+00:00

Abstract

For IoT applications, this work presents an analytical study of large-scale RFID tag inventory methods. First, it introduces the fundamental principles of RFID systems, with particular emphasis on large-scale RFID tag inventory methods, and analyzes the key issues in tag inventory, including mobile tag identification, missing tag detection, and unidentified tag detection. Second, from the perspective of realistic channel environments, it provides a focused survey of the current research landscape of tag inventory methods, encompassing comparative analyses of mobile tag identification methods, missing tag detection methods, and unidentified tag detection methods, while identifying the principal challenges in this domain and offering recommendations for future research.

Full Text

Preamble

Title: Research on Large-Scale RFID Tag Inventory Methods in the Internet of Things

Authors: Chen Yihong, Wang Jin, He Chunlin, He Jialin

Affiliation: IoT Perception & Distribution Processing Institute, China West Normal University, Nanchong, Sichuan 637002, China

Abstract: For IoT applications, this paper analyzes and studies large-scale RFID tag inventory methods. First, it introduces the basic principles of RFID systems, particularly large-scale RFID tag inventory methods, and analyzes the problems involved in tag inventory, including mobile tag identification, missing tag monitoring, and unknown tag monitoring. Second, from the perspective of realistic channel environments, it respectively reviews the current research status of tag inventory methods, including comparative analysis of mobile tag identification methods, missing tag monitoring methods, and unknown tag monitoring methods, and identifies the main problems in this field while providing suggestions for future research.

Keywords: RFID; mobile tag; missing tag; unrecognized tag; monitoring

0 Introduction

RFID (Radio Frequency Identification) is a widely applied automatic identification technology. An RFID system consists of readers (also called inventory devices) and numerous tags, with actual systems also including a server with a tag ID database. The reader automatically identifies objects by obtaining data stored in tags via wireless signals, then networks these identified objects to build IoT application systems. RFID offers unparalleled advantages over other automatic identification technologies because it can scan and identify multiple tags simultaneously at long range and within non-line-of-sight environments. Currently, RFID has become a research hotspot worldwide and is applied across various industries such as supply chain management [1] and warehouse management [2,3].

The IoT system comprises a sensing layer, network layer, and application layer, with sensing layer technology as its foundation. RFID serves as the primary sensing layer technology. As a new generation of information technology, IoT is increasingly applied in numerous domains including food traceability, intelligent logistics, intelligent transportation, production line management, and rail transit [1], thereby promoting social development and economic transformation. In recent years, to further advance IoT technology development and application, national policies have been implemented to accelerate research and development of IoT and related technologies.

In RFID systems, the tag collision problem is a fundamental issue that scholars have studied for many years, continuously achieving new progress [4-6]. However, as RFID applications become increasingly widespread, new application modes continue to emerge [7-8], among which large-scale RFID tag inventory represents a broadly applicable and representative pattern. RFID tag inventory primarily includes tag entry/exit operations and inventory checking, as illustrated in [Figure 1: see original paper]. At warehouse entrances, readers identify newly arrived (unknown) tags using mobile tag identification protocols, storing their IDs in the TagID Database, thereby converting them to known tags. When known tags exit the warehouse, readers similarly read their IDs at entrances and delete them from the database, converting them back to unknown tags. Readers check inventory by discovering missing tags and unknown tags—the former may result from theft, while the latter may appear when tags mistakenly enter the warehouse or when readers miss newly arrived tags. Readers can respectively employ missing tag monitoring methods and unknown tag monitoring methods to discover these cases.

In realistic channel environments, noise can be confused with short responses, and erroneous transmission of frame preamble vectors can cause unknown tag discrimination mechanisms to fail. If readers mistakenly interpret interference signals as tag short responses, false positive problems occur. Conversely, if unknown tag responses are lost, false negative problems arise.

1.1 Mobile Tag Identification

During tag entry and exit processes, if readers cannot promptly identify arriving or departing tags, tag misreading occurs, causing the ID database to inaccurately reflect actual warehouse tag presence. Therefore, researching high-identification-rate mobile tag identification protocols is crucial. However, realistic channels suffer from packet reception failures due to interference and noise, as well as bit errors and capture effect problems. Additionally, time constraints for identifying mobile tags as they enter or exit the reader’ s field of view affect identification rates. This raises the fundamental question: how can we develop high-identification-rate mobile tag identification protocols that address packet reception failures, bit errors, and capture effects in realistic channels? Solving this problem is both the foundation and key challenge in tag inventory method research.

1.2 Missing Tag Monitoring

When a known tag ID exists but the reader receives no response from that tag, the tag is judged missing. Two approaches exist: detecting tag loss events and identifying specific missing tags. The former probabilistically detects loss events with certain accuracy, while the latter deterministically identifies all missing tag IDs, requiring greater time overhead. In practice, these two approaches complement each other—the former detects loss events, then the latter confirms them, thereby improving missing tag discovery capability and efficiency. However, if readers mistakenly consider non-missing tags as missing, false negative problems occur. Conversely, failing to discover actually missing tags creates false positive problems. During missing tag identification and detection, if normal tags exit the warehouse but the ID database cannot be updated in time, false missing tag reports occur. Therefore, minimizing missing tag identification and detection time is critical. Interference in unreliable channels can cause packet reception failures, leading to false missing tag reports and false negative problems. When tags are actually missing and should not respond, readers may misinterpret channel noise as short responses from missing tags, incorrectly reporting tag presence and causing false positive problems.

1.3 Unknown Tag Monitoring

Readers must use tag short responses and frame preamble vectors to discriminate unknown tags. Two approaches exist: detecting unknown tag events and identifying specific unknown tags. The former probabilistically detects unknown tag events with certain accuracy, while the latter deterministically identifies all unknown tag IDs, requiring greater time overhead. In practice, these approaches complement each other—the former detects events, then the latter confirms them, improving unknown tag discovery capability and efficiency. However, in realistic channel environments, noise confusion with short responses and erroneous transmission of frame preamble vectors can cause discrimination mechanism failure. If readers mistakenly interpret interference signals as tag short responses, false positive problems occur. Conversely, if unknown tag responses are lost, false negative problems arise.

2.1 Mobile Tag Identification Strategies

a) **Tag Movement Strategies:** Identification protocols support two tag movement classes: conveyor belt-based constant-speed, fixed-density tags moving along fixed routes, and freely moving ordinary tags. Conveyor belt-based identification protocols need not know or control tag distribution beforehand; the key problem is adjusting conveyor speed to achieve higher mobile tag identification rates. Although these protocols study mobile tag identification, they do not address uncontrolled, freely moving ordinary tags. Clearly, conveyor belt-supported protocols cannot apply to ordinary tag movement environments. Yet with IoT RFID application development, such universal mobile environment applications are becoming increasingly common.

b) **Identification Mechanism Strategies:** Basic identification mechanisms employed by protocols fall into two categories: TREE and DFSA. Among TREE-based mobile tag identification protocols, both ABS and PRB improve upon BS to support tag arrival and departure, while QSA modifies QT to identify mobile tags. However, BS and QT protocols suffer long identification delays and low time efficiency, approximately 40% and 41% respectively. Since DFSA mechanisms more easily support tag arrival by selecting frame slots for participation, most mobile tag identification protocols adopt DFSA. Analysis of existing DFSA-based protocols reveals numerous idle and collision slots during mobile tag identification, yielding average system identification efficiency of only approximately 36.8%. Only a few protocols using unequal slot durations improve time efficiency to 70%.

c) **Target Performance Strategies:** Most protocols target mobile tag identification rate, while a few target identification efficiency and throughput. These performance metrics are essentially consistent—higher identification efficiency or throughput yields higher identification rate. However, since identification rate is the key metric for mobile tag identification, directly using it as the design target more easily achieves high identification rates.

d) **Identification Order Strategies:** Scientifically arranging tag identification order in mobile environments helps reduce tag misreading rates.

Existing protocols employ either random identification or grouped identification. Grouping methods include grouping by arrival time, by tag type priority, or by deadline. Random identification, which ignores arrival order, easily causes tag misreading. Various grouped identification methods consider arrival order but use coarse-grained groups, causing later-arriving tags to be identified before earlier ones and resulting in tag misreading.

e) **Realistic Wireless Channel Environment Issues:** Data packet reception failures and capture effects exist in realistic wireless channel environments.

2.2 Comprehensive Analysis of Mobile Tag Identification Protocols

Based on the above mobile tag identification strategies, this paper comprehensively analyzes and compares major mobile tag identification protocols from perspectives including movement type, identification mechanism, target performance, identification order, packet reception failure, and capture effect. presents the analysis results.

2.3 Existing Problems and Future Research Directions

Comprehensive analysis of mobile tag identification protocols reveals that existing protocols do not simultaneously consider packet reception failure, bit errors, and capture effects. Moreover, their analytical models do not incorporate these factors, so optimized parameters cannot reflect these realistic channel constraints simultaneously, making it difficult to obtain truly effective optimal identification rates. Existing protocols' basic identification mechanisms suffer numerous idle and collision slots with identification efficiency of only about 36.8%. Additionally, these protocols primarily identify mobile tags in random or coarse-grained group order, causing misreading problems that significantly affect mobile tag identification rates.

Future research should focus on supporting freely moving tag identification with broad applications, considering objectively existing packet reception failure and capture effects in realistic channel environments, designing high-efficiency DFSA mechanisms, and employing fine-grained ordering based on tag arrival sequence to further reduce tag misreading rates. This represents the primary future research direction in this field.

3.1 Missing Tag Monitoring Strategies

a) **Missing Monitoring Strategies:** Tag loss detection protocols are probabilistic, enabling rapid discovery of tag loss events, while missing tag identification protocols are deterministic, aiming to learn all missing tag IDs at greater time cost. These two approaches have complementary advantages and disadvantages.

b) **Tag Scope Strategies:** The number of tags participating in detection and identification measures overall system energy. The all-tags approach suits widely used low-cost passive tags, while sampling and classification involve only partial tags, suiting specific high-cost active tags.

c) **Target Performance Strategies:** Some protocols consider energy consumption and time as target performance for active tag applications, while others consider only time. The former requires trade-offs between two metrics, while the latter faces fewer constraints and can reduce time overhead further.

d) **Frame Preamble Vector Strategies:** Readers use frame preamble vectors containing known tag signals to enable unknown tags in their vicinity to transmit their IDs or short responses for identification or detection. Therefore, reliable transmission of frame preamble vectors to tags is critical, yet current protocols do not consider packet reception failure in realistic channel environments.

e) **Response Length Strategies:** When readers issue query commands individually, tags may respond with their IDs, allowing immediate unknown tag determination through ID database comparison. Alternatively, tags may first respond with short responses; after receiving these, readers command tags to transmit their IDs based on circumstances. The former mainly suits unknown tag identification protocols with greater time and energy costs, while the latter using only short responses consumes less energy and suits unknown tag detection protocols.

f) **Realistic Wireless Channel Environment Issues:** Data packet reception failures exist in realistic wireless channel environments.

3.2 Comprehensive Analysis of Missing Tag Monitoring Protocols

Based on the above missing tag monitoring strategies, this paper comprehensively analyzes and compares major missing tag monitoring protocols from perspectives including monitoring approach, participating tag scope, target performance, frame preamble vector, response length, packet reception failure, and capture effect. presents the analysis results.

3.3 Existing Problems and Future Research Directions

Comprehensive analysis of missing tag monitoring protocols reveals that some protocols qualitatively analyze the impact of packet reception failure caused by unreliable channels, but the protocol mechanisms do not consider reception failure, and performance analysis models do not incorporate reception failure factors. This causes tag loss discrimination mechanisms to fail, preventing guaranteed detection and identification accuracy and making it difficult to obtain truly effective optimal protocol parameters and performance. Existing protocols use short responses to discriminate missing tags. However, when the distance between readers and tags is large, short responses easily confuse with noise, causing false positive and false negative problems that risk discrimination mechanism failure.

Future research in this field should consider objectively existing packet reception failure and capture effects in realistic channel environments, designing noise-resistant long responses with multi-bit checksums to solve false positive and false negative problems. Additionally, existing protocols only discriminate missing tags in expected single-tag slots, wasting multi-tag slots, so research should improve slot utilization efficiency. Designing noise-resistant short responses, minimizing polling while maximizing use of designed short responses, avoiding frame preamble vector transmission between readers and tags, utilizing collision slots to increase missing tag detection and identification opportunities, and incorporating capture effects and reception failure factors into protocol analysis models will yield effective protocol parameters and optimal identification performance.

4.1 Unknown Tag Monitoring Strategies

a) **Unknown Monitoring Strategies:** Unknown tag detection protocols are probabilistic, enabling rapid discovery of unknown tag events, while unknown tag identification protocols are deterministic, aiming to learn all unknown tag IDs at greater time cost. These two approaches have complementary advantages and disadvantages.

b) **Tag Scope Strategies:** The number of tags participating in detection and identification measures overall system energy. The all-tags approach suits widely used low-cost passive tags, while sampling and classification involve only partial tags, suiting specific high-cost active tags.

c) **Target Performance Strategies:** Some protocols consider energy consumption and time as target performance for active tag applications, while others consider only time. The former requires trade-offs between two metrics, while the latter faces fewer constraints and can reduce time overhead further.

d) **Frame Preamble Vector Strategies:** Readers use frame preamble vectors containing known tag signals to enable unknown tags in their vicinity to transmit their IDs or short responses for identification or detection. Therefore, reliable transmission of frame preamble vectors to tags is critical.

e) **Tag Response Strategies:** After readers issue query commands, tags may respond with their IDs or first with short responses. Upon receiving short responses, tags transmit their IDs based on reader commands. The former mainly suits unknown tag identification protocols with greater time and energy costs, while the latter using only short responses consumes less energy and suits unknown tag detection protocols.

f) **Realistic Wireless Channel Environment Issues:** Data packet reception failures exist in realistic wireless channel environments.

4.2 Comprehensive Analysis of Unknown Tag Monitoring Protocols

Based on the above unknown tag monitoring strategies, this paper comprehensively analyzes and compares major unknown tag monitoring protocols from perspectives including monitoring approach, target performance, frame preamble vector, tag response, and packet reception failure. presents the analysis results.

4.3 Existing Problems and Future Research Directions

Comprehensive analysis of unknown tag monitoring protocols reveals that erroneous transmission of frame preamble vectors in realistic channel environments can cause known tags to interfere with unknown tag identification and miss detecting unknown tags, thereby reducing unknown tag identification efficiency and detection probability. Currently, protocols using frame preamble vectors do not address or analyze erroneous vector transmission problems. Confusion between short responses and realistic channel noise causes discrimination mechanism failure. Unknown tag detection protocol mechanisms do not consider erroneous frame preamble vector transmission or reader packet reception failure for unknown tag responses, and protocol analysis models do not incorporate bit error rates and reception failure rates. Therefore, they cannot obtain truly effective optimal parameters or performance in realistic channel environments. Existing protocols discriminate unknown and known tags only in single-tag slots, wasting other slots and resulting in low protocol efficiency. Future research should address packet reception failure problems in realistic channels, design improved protocol mechanisms to overcome resulting false positive and false negative problems, and incorporate stochastic probability factors into protocol analysis mathematical models.

5 Conclusion

Through analysis of strategies employed by three tag inventory methods and detailed comparative analysis of existing methods based on these strategies, we find that: (a) existing mobile tag identification protocols have low basic identification mechanism efficiency and identify mobile tags in random or coarse-grained group order, which reduces mobile tag identification rates; (b) existing missing tag monitoring and unknown tag monitoring protocols rarely consider data reception loss and capture effects in wireless channels, causing discrimination mechanism failure and difficulty guaranteeing detection and identification accuracy; (c) protocol analysis models for all three tag inventory methods do not incorporate realistic channel factors of packet loss, bit errors, and capture effects, making it difficult to obtain truly effective protocol parameters in realistic channel environments, preventing protocols from operating at optimal performance.

Future research in this field should consider data packet reception failure, bit errors, and capture effects in realistic channel environments to design reliable tag identification and monitoring protocol mechanisms. Based on these factors, mathematical analysis models should be established to obtain optimal protocol parameters, leading to the development of large-scale RFID tag inventory methods with good robustness, high identification rates, fast speeds, and high accuracy.

References

[1] 吴敏. 基于 RFID 技术在轨道交通中的应用 [J]. 自动化博览, 2017, 14 (4): 100-103.

[2] Zheng Yuanqing; Li Mo. Towards more efficient cardinality estimation for large-scale RFID systems [J]. IEEE Transs on Networking, 2014, 21 (6): 1905-1908.

[3] Zheng Y, Li M. Fast tag searching protocol for large-scale RFID systems [C]// Proc of IEEE International Conference Network Protocols. 2011: 363-372.

[4] Wu Haifeng, Zeng Yu, Feng Jihua, et al. Binary tree slotted ALOHA for passive RFID tag anticollision [J]. IEEE Trans on Parallel and Distributed Systems, 2013, 24 (1): 19-31.

[5] 张小红, 张留洋. RFID 防碰撞时隙应变协处理算法研究 [J]. 电子学报, 2014, 42 (6): 1139-1146.

[6] Chen Yihong, Feng Quanyuan, Ma Zeng, et al. Multiple-bits-slot reservation aloha protocol for tag identification [J]. IEEE Trans on Consumer Electronics, 2013, 59 (1): 93-100.

[7] Yang Zhipeng, Ning Ting, Wu Hongyi. Distributed data query in intermittently connected passive RFID networks [J]. IEEE Trans on Parallel and Distributed Systems, 2013, 24 (10): 1972-1982.

[8] Xie Lei, Han Hao, Li Qun, et al. Efficient protocols for collecting histograms in large-scale RFID systems [J]. IEEE Trans on Parallel and Distributed Systems, doi: 10. 1109//TPDS. 2014. 2357021.

[9] Khandelwal G, Yener A, Lee K, et al. A MAC protocol for dense and time constrained RFID systems [C]// Proc of IEEE International Conference on Communications. 2006: 4028-4033.

[10] Myung J, Lee W, Srivastava J, et al. Tag-splitting: adaptive collision arbitration protocols for RFID tag identification [J]. IEEE Trans on Parallel and Distributed Systems, 2007, 18 (6): 763-775.

[11] Sarangan V, Devarapalli M R, Radhakrishnan S. A framework for fast RFID tag reading in static and mobile environments [J]. Computer Networks, 2008, 52: 1058-1073.

[12] Lai Y, Lin C. Two blocking algorithms on adaptive binary splitting: Single and pair resolutions for RFID tag identification [J]. IEEE//ACM Trans on Networking, 2009, 17 (3): 962-975.

[13] Xie Lei, Sheng Bo, Tan C C, et al. Efficient tag identification in mobile RFID systems [C]// Proc of IEEE INFOCOM. 2010.

[14] Sheng Bo, Li Qun, Mao Weizhen. Efficient continuous scanning in RFID systems [C]// Proc of IEEE INFOCOM. 2010.

[15] Lee C C, Lin Shengyue. A double blocking dynamic framed slotted ALOHA anti-collision method for mobile RFID systems [C]// Proc of International Conference on Genetic and Evolutionary Computing. 2012: 581-584.

[16] 陈毅红; 冯全源. 物联网中标签持续到达的 RFID 防碰撞算法 [J]. 计算机集成制造系统, 2012, 18 (9): 2076-2081.

[17] Benedetti D, Maselli G, Petrioli C. Fast identification of mobile RFID tags [C]// Proc of IEEE International Conference on Mobile Ad hoc and Sensor Systems. 2012: 65-74.

[18] Li Xiaowu, Feng Quanyuan. An improved EPC class 1 gen 2 protocol with FCFS feature in the mobile RFID systems [J]. International Journal of Computers Comunications & Control, 2013, 8 (6): 854-862.

[19] Li Xiaowu, Feng Quanyuan. Grouping based dynamic framed slotted ALOHA for tag anti-collision protocol in the mobile RFID systems [J]. Applied Mathematics & Information Sciences, 2013, 7 (2L): 655-659.

[20] Gao Jianliang, Wang Jianxin, He Jianbiao. QSA: query splitting-based anticollision for mobile RFID-based Internet-of-things [J]. International Journal of Distributed Sensor Networks, 2013.

[21] Zhu Weiping, Cao Jiannong, Chan H C B, et al. Mobile RFID with a high identification rate [J]. IEEE Trans on Computers, 2014, 63 (7): 1778-1792.

[22] Park C W, Ahn J H, Lee T J. A protocol minimizing missing tags in a moving RFID tag environment [J]. International Journal of Information and Electronics Engineering, 2014, 4 (3): 244-248.

[23] Chen Yihong; Feng Quanyuan. An efficient anti-collision algorithm for the EPC global class-1 generation-2 system under the dynamic environment [J]. KSII Trans on Internet and Information Systems, 2014, 8 (11): 3997-4015.

[24] Li Tao, Chen Shigang, Ling Yibei. Efficient protocols for identifying the missing tags in a large RFID system [J]. IEEE Trans on Networking, 2013, 21 (6): 1974-1987.

[25] Tan C C, Sheng Bo, Li Qun. Efficient techniques for monitoring missing RFID tags [J]. IEEE Trans on Wireless Communications, 2011, 9 (6): 1882-1890.

[26] Li Tao, Chen Shigang, Ling Yibei. Identifying the missing tags in a large RFID system [C]// Proc of the 11th ACM International Symposium on Mobile Ad hoc Networking and Computing. New York: ACM Press, 2010: 1-9.

[27] Luo Wen, Chen Shigang, Li Tao, et al. Efficient missing tag detection in RFID systems [C]// Proc of IEEE INFOCOM. 2010: 356-360.

[28] Luo Wen, Chen Shigang, QiaoYan, et al. Missing-tag detection and energy-time tradeoff in large-scale RFID systems with unreliable channels [J]. IEEE Trans on Networking, 2014, 22 (4): 1079-1091.

[29] Liu Xiulong, Li Keqiu, Min Geyong, et al. A multiple hashing approach to complete identification of missing RFID tags [J]. IEEE Trans on Communications, 2014, 62 (3): 1046-1057.

[30] Zhao Jumin, Li Wenting, Li Deng' ao. Identifying the missing tags in categorized RFID systems [J]. International Journal of Distributed Sensor Networks, 2014, http://dx. doi. org/10. 1155/2014/582951.

[31] Liu Xiulong, Li Keqiu, Min Geyong, et al. Completely pinpointing the missing RFID tags in a time-efficient way [J]. IEEE Trans on Computers, 2015, 64 (1): 87-96.

[32] Zhang Rui, Liu Yunzhong, Zhang Yanchao, et al. Fast identification of the missing tags in a large RFID system [C]// Proc of IEEE Communications Society Conference on Sensor, Mesh and Ad hoc Communications and Networks. 2011: 278-286.

[33] 张士庚, 刘光亮, 刘璇, 等. 大规模 RFID 系统中一种能量有效的丢失标签快速检测算法 [J]. 计算机学报, 2014, 37 (2): 434-444.

[34] Sheng Bo, Li Qun, Mao Weizhen. Efficient continuous scanning in RFID systems [C]// Proc of IEEE INFOCOM. 2010.

[35] Liu Xuan, Zhang Shigeng, Bu, Kai. Complete and fast unknown tag identification in large RFID systems [C]// Proc of IEEE International Conference on Mobile Ad-hoc and Sensor Systems. 2012: 47-55.

[36] Liu Xiulong, Li Keqiu, Min Geyong. Efficient unknown tag identification protocols in large-scale RFID systems [J]. IEEE Trans on Parallel and Distributed Systems. 2014, 25 (12): 3145-3155.

[37] Liu Xiulong, Qi Heng, Li Keqiu, et al. Time-and energy-efficient detection of unknown tags in large-scale RFID systems [C]// Proc of IEEE International Conference on Mobile Ad-hoc and Sensor Systems. 2013: 95-103.

Note: Figure translations are in progress. See original paper for figures.