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A Spatially Aware RFID-Enhanced Wireless Sensor Network

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Abstract

Radio frequency identification (RFID) systems are becoming increasingly popular for automatic object identification and supply chain management. Wide acceptance of this technology has led to several new areas of research, one of which is RFID-enhanced wireless sensor networks (WSNs). Such networks have the ability to self-organize, identify tagged objects, perform localization, and carry out searches; all of which are enablers of pervasive computing. This paper therefore presents various challenges to creating such networks, and describes our recent research on energy efficient RFID tag reading protocols.

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A Spatially Aware RFID-Enhanced Wireless Sensor Network

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***Abstract*— Radio frequency identification (RFID) systems are becoming increasingly popular for automatic object identification and supply chain management. Wide acceptance of this technology has led to several new areas of research, one of which is RFID-enhanced wireless sensor networks (WSNs). Such networks have the ability to self-organize, identify tagged objects, perform localization, and carry out searches; all of which are enablers of pervasive computing. This paper therefore presents various challenges to creating such networks, and describes our recent research on energy efficient RFID tag reading protocols.**

I. Introduction

In recent years, radio frequency identification (RFID) has gained enormous publicity, especially after both Wal-Mart and the Department of Defense mandated their respective suppliers use RFID tags in an effort to cut logistical costs [29][28]. The key advantage of RFID is its ability to identify multiple objects wirelessly without direct line of sight. Moreover, the versatility of RFID tags in terms of their shapes, sizes, ranges, and types make them far superior to conventional bar codes. In-Stat [14] predicts that more than 33 billion tags will be produced globally by 2010, which is 25 times the number of tags produced in the year 2005. This increasing interests in RFID technology has brought forth a number of research areas. One of which is RFID-enhanced WSNs.

RFID-enhanced WSNs consist of sensor nodes equipped with an RFID reader. They enjoy several benefits. Specifically, given the size of sensor nodes and self-organizing abilities, they can be used to instrument a physical space easily to track animate or inanimate objects. As a result, several interesting applications have emerged. Ho et al. [12] outlined an in-home elder healthcare system that uses sensor nodes equipped with an RFID reader to monitor patients' medication intake. In a similar work, Intel [15] developed a system to monitor an elder's activities by recording the number of times an RFID-tagged item is touched. In [25], NASA/JPL outlined a project to develop a web of sensors equipped with a RFID reader that monitor and respond to environment changes. Finally, BP Oil [30] is using RFID-enhanced sensor nodes for location tracking and to sense the working conditions of machines.

The aforementioned projects, however, have only reported on system issues pertaining to RFID-enhanced WSNs. Many challenges remain. Some of which include those in the following research areas: 1) energy efficient tag reading and monitoring protocols, 2) scalable and resource efficient techniques for managing tag IDs, 3) tags coverage, and 4) GPS-less localization algorithms.

Before delving further into the above areas in Section III, we first present an overview of RFID and WSNs in Section II-A and II-B respectively.

II. Background

A. Radio Frequency Identification

RFID or Radio Frequency IDentification tracks objects using magnetic or electromagnetic response exchange. It consists of an RFID reader, and a finite number of tags; see Figure 1. An RFID reader is usually a powerful device with ample computational and memory resources. RFID tags, on the other hand, are designed with severe cost limitations, hence they have a simple design [10].

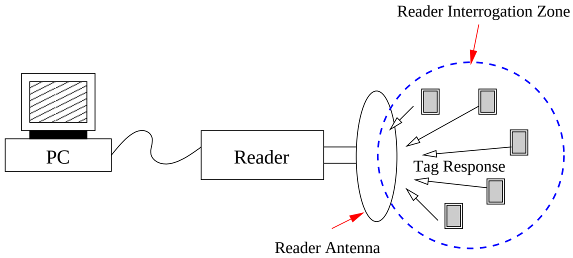

Fig. 1. Interactions between a reader and tags.

RFID tags can be categorized into three types: active, passive, or semi-passive [10]. Passive tags have the lowest complexity, no power source nor an on-tag transmitter. In contrast, semi-passive tags have an on-board power source to energize their microchip. Both passive and semi-passive tags rely on the reader's energy to transmit their ID. However, none of them have the ability to sense the channel. Lastly, active tags have an on-board power source and a transceiver. They can sense the channel and are able to operate without a reader.

Passive and semi-passive tags are cheap compared to active tags [10] and are therefore suitable for large scale deployments. However, RFID systems using passive and semi-passive tags suffer from two key problems: *tag collision*, and *reader collision*.

Tag collisions arise when multiple tags respond simultaneously to a reader's request, thereby causing collisions at

the reader, leading to bandwidth and energy wastage, and prolonged tag identification time [32].

The reader collision problem results from overlapping reader interrogation zones [8], and can be further subdivided into reader-to-tag and reader-to-reader interference problems. In the former, a collision results when two or more readers attempt to communicate with a tag. As a result, tags are unable to distinguish requests from their respective reader; as shown in Figure 2. In the later, readers with overlapping interrogation zones are unable to receive replies from tags, see Figure 3.

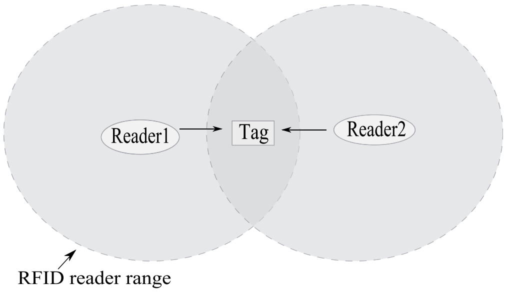

Fig. 2. Reader-to-Tag.

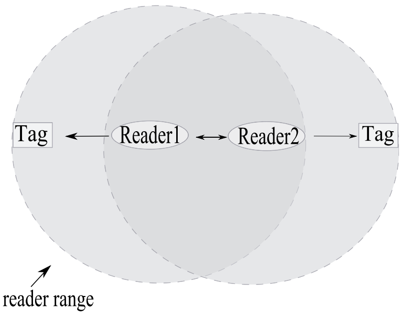

Fig. 3. Reader-to-Reader.

B. *RFID Enhanced WSNs*

Advances in Micro-Electro-Mechanical Systems (MEMS) over the last few years have resulted in the development of networks comprising of wireless sensor nodes [13]. These nodes are small in size, cheap, and have a variety of sensing modules. Moreover, they have limited computational power and memory. Other key properties include the ability to self-organize and form multi-hop networks with little human intervention.

A recent development in the area of WSNs is the coupling of a RFID reader to a wireless sensor node to create RFID enhanced WSNs, which can then be used to instrument a physical space. Take for example a library or a warehouse. RFID enhanced sensor nodes can be embedded into the infrastructure to track tagged items and provide users with a detail map of assets. Such application is a marked departure from current RFID systems, and also those in WSNs that have thus far limited to using conventional sensing elements such as temperature, humidity, motion, etc. Lastly, with the advent of SkyeTek's RFID reader [33] that mates with Crossbow's MICA2Dot sensor motes [7], RFID enhanced WSNs have become commercially viable.

III. Research Issues

A. *Tag Reading*

Tag reading protocols are used by RFID readers to address the tag collision problem. They are highly optimized to ensure quick and efficient tag reading. Unfortunately, they are not energy efficient; a key concern in RFID enhanced WSNs.

In [18], we analyzed the energy consumption of a sensor mote with an RFID reader. We observed that an RFID reader while scanning 96-bits of tag ID consumes higher energy compared to a sensor node receiving and transmitting the same amount of data. Moreover, as a reader's scanning/reading duration increases, so does its energy consumption.

The above result motivates the development of energy efficient tag reading protocols. In particular, those that have low complexity, fast, efficient, and energy aware. In this respect, we have investigated Pure and Slotted Aloha, and Framed Aloha based tag reading protocols. In addition, we have also studied tag estimation functions, which are used by Frame Aloha protocols to adjust their frame size after each read. To date, our key results are as follows:

1) Among six variations of Pure and slotted Aloha based protocols, slotted Aloha with muting and early-end consumes the lowest energy. This is primarily due to the muting and early-end feature. The former silences a tag after identification whereas the later causes a reader to close an idle slot early. We found that these two features significantly reduce the number of collisions and wastage due to idle slots, which in turn minimize the energy consumed by a reader. However, we observed that the early-end feature is only effective when the number of tags is low. This means as the number of tags increases, its benefits diminishes [18].
2) Among twelve variations of framed slotted Aloha (FSA) protocols, we found that dynamic FSA with muting and early-end has the lowest energy consumption for both low and high tag density environments [20].
3) Dynamic FSA protocols have the ability to adjust their frame size with changing tag population. This is done with the help of a tag estimation function. An accurate estimate ensures an optimal frame size is used to read tags, thereby achieves the lowest identification delay [19]. In this respect, we have compared the accuracy of five tag estimation functions, and found that the function proposed by Vogt [34], which is based on Chebychev's inequality, achieves the best accuracy for a wide range of tags. On the other hand, a function proposed by Cha et al. [5] for muting based environments is more accurate when the number of tags is higher than the frame size used to read them [19].

In addition to the results above, a key observation is that the orientation of tags dictates an RFID reader's read range. In the worst case, if a tag's antenna is parallel to the reader field lines, tags become unreadable [10][21]. This means when

readers and tags are deployed randomly, there is a possibility that some tags will be unreadable even though they are in a reader's interrogation zone.

An approach to overcome the above problem is to develop cooperative tag reading protocols. In essence, we are interested in having multiple RFID-enhanced sensor nodes with overlapping interrogation zone read a set of tags. The observation here is that given the diversity of sensor node locations, it is likely that one of them will be better oriented to read tags that otherwise would be unreadable if there is only one reader. The development of such protocol is currently in progress.

In Section II-A, we highlighted two key problems that occur in multiple readers systems. So far only a handful of solutions exist [35][2][1][9][11]. All of them, however, have been developed in the context of conventional RFID systems. None of them consider energy efficiency, discrepancies in transmission range of RFID readers compared to sensor nodes, and the multi-hop nature of WSNs.

B. Monitoring

An important consideration in RFID-enhanced WSNs is tracking identified tags. This problem is particularly acute when tag population changes frequently. Unfortunately, existing protocols are inefficient and not scalable. They either have to re-read all tags again [34][36][5], or require expensive tree reconstruction [23][24][6][17][16]. Hence, there is a clear need for energy efficient protocols that can determine new and old tags quickly. Moreover, such protocols must be energy efficient in dynamic and high tag density environments.

In this respect, we have developed an energy efficient monitoring protocol that uses three distinct frames to identify, read and monitor tags. The first frame, called the reservation frame, is used to allocate a unique slot in the forthcoming body frame, where tags transmit their full ID in a collision free manner. After all tags are identified, the reader then tracks them by sending out monitor frames periodically. A key feature of the proposed protocol is that tags only need to transmit a small number of bits during the reservation and monitor frames instead of their full ID. This minimizes collisions as well as reduces scanning duration, both of which cut energy expenditure significantly. We are currently conducting simulation studies, and results will be available soon.

C. Coverage

The read range of RFID readers is much smaller than a typical sensor node's transmission range. Hence, when deploying RFID-enhanced sensor nodes, if the discrepancy in transmission range is not taken into account, a large number of tags will be excluded, i.e., they may not be in the interrogation zone of any RFID readers. Thus, the challenge is develop coverage protocols that ensure all tags are readable, and also address the tag orientation and reader collision problems outlined in Section III-A.

The coverage problem has been tackled extensively in WSNs, see [22] for examples, but only a handful of works exist for RFID systems. Thus far, none of them, e.g., [4], have considered the discrepancies in transmission/reading range. Therefore, the development of a coverage algorithm suitable for RFID-enhanced WSNs will be an important contribution.

D. Search and Storage

The number of RFID-enhanced sensor nodes deployed in a region is application dependent. It can be as low as say ten nodes for monitoring items in a small office to thousands of nodes to monitor bush fires. Hence, depending on the application and data collection protocol, different amounts of memory and energy will be required to store and forward tag IDs to a sink. This is even more critical for nodes that are near a sink node.

To avoid flooding tag IDs, a possible approach is to employ distributed hash tables (DHTs) [31]. Each sensor node maintains hashes of tag IDs, and also keys to hashes maintained by other nodes. In order to retrieve a tag ID, a user submits the key corresponding to the item to the WSN, which will then route it directly to a sensor node responsible for the item. The user can therefore quickly determine whether an item exists.

Although DHTs look promising, there are many open research problems. Namely, (a) physical mapping, (b) load balancing, and (c) support for multiple attributes. Existing approaches do not guarantee information corresponding to a key will be stored at a sensor node that is near the item's physical location. This is important because searches and updates need to be carried out quickly, preferably using the resources of only a few sensor nodes. On the other hand, given the memory and battery constraints of each sensor node, we need to ensure tag information is stored across all sensor nodes to ensure the collective buffer of sensor nodes are utilized efficiently, and also to reduce the number of queries directed at a particular nodes. Apart from that, DHTs do not readily support wildcard searches, for example searching for books with title matching "wireless" or/and "sensor".

E. Localization

After performing a search and being informed that an item exists, a user may want to determine its location. For example, in a library setting, the RFID-enhanced WSN may inform the user on a predefined map the location of a book. Alternatively, the WSN may 'guide' the user to the location of a book by switching on/off lights near the book.

In the past few years, localization has received a lot of attention; see for example [3] [26] [27]. The challenge, however, is obtaining accurate measurements in indoor settings. Moreover, given the limited computational capabilities, and low energy requirements of sensor nodes, any localization solution cannot rely on GPS. In this respect, localization approaches that use anchor points with predefined coordinates may prove practical [3]. In addition, any localization protocol employed will have to work with protocols outlined in Section III-C.

IV. Conclusion

In this paper, we have presented five key research areas that underpin the realization of RFID-enhanced WSNs. Our research is currently focused on energy efficient tag reading

protocols. We believe that the development of such protocols is critical, and their performance will significantly affect protocols developed in other research areas. To date, our research has identified key energy consumption factors, and quantified the energy efficiency and limitations of existing tag reading protocols. From these findings, we have developed a new energy efficient tag reading protocol that is capable of reading and monitoring tags quickly. Results are forthcoming.

V. Acknowledgment

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References

[1] Alien technology, EPCglobal Class 1 Gen 2 RFID Specifications. Whitepaper. http://www.alientechnology.com/docs/AT_wp_EPCGlobal_WEB.pdf.

[2] S. M. Birari and S. Iyer. Mitigating the Reader Collision Problem in RFID Networks with Mobile Readers. In *The 13th IEEE International Conference on Networks*, Kuala Lumpur, Malaysia, 2005.

[3] N. Bulusu, J. Heidemann, and D. Estrin. GPS-less low cost outdoor localization for very small devices. *IEEE Personal Communications Magazine*, 7(5):28–34, 2000.

[4] B. Carbunar, M. K. Ramanathan, M. Koyuturk, C. Hoffmann, and A. Rama. Redundant Reader Elimination in RFID Systems. In *IEEE SECON*, pages 176–184, Santa Clara, CA, USA, Sept. 2005.

[5] J.-R. Cha and J.-H. Kim. Novel Anti-collision Algorithms for Fast Object Identification in RFID System. In *The 11th Intl. Conference on Parallel and Distributed Systems*, pages 63–67, 2005.

[6] W.-C. Chen, S.-J. Horng, and P. Fan. An Enhanced Anti-collision Algorithm in RFID Based on Counter and Stack. In *Second Intl. Conf. on in Systems and Networks Communications (ICSNC 2007)*, pages 21–24, Cap Esterel, France, Aug. 2007.

[7] Crossbow. Mica2. Webpage. http://www.xbow.com/Products/Product_pdf_files/Wireless_pdf/MICA2_Datasheet.pdf.

[8] D. W. Engels and S. E. Sarma. The Reader Collision Problem. In *IEEE Intl. Conf. on Systems, Man and Cybernetics*, Tunisia, Oct. 2002.

[9] ETSI. ETSI EN 302 208-1 V1.1.1. Standard. http://www.rfidc.com/pdfs_downloads/ETSI%20Standard.pdf.

[10] K. Finkenzeller. *RFID Handbook , Fundamentals and Apps. in Contactless Smart Cards and Identification*. John Wiley and Sons Ltd., 2003.

[11] J. Ho, D. Engels, and S. Sarma. HiQ: a Hierarchical Q-learning Algorithm to Solve the Reader Collision Problem. In *International Symposium on Applications and the Internet Workshops (SAINTW'06)*, Jan. 2006.

[12] L. Ho, M. Moh, Z. Walker, T. Hamada, and C.-F. Su. A Prototype on RFID and Sensor Networks for Elder Healthcare: Progress Report. In *Proceeding of the 2005 ACM SIGCOMM workshop on Experimental approaches to wireless network design and analysis*, pages 70–75, Philadelphia, Pennsylvania, USA, 2005. ACM Press.

[13] M. Ilyas and I. Mahgoub. *Handbook of Sensor Networks: Compact Wireless and Wired Sensing Systems*. Taylor and Francis Group, 1970.

[14] In-Stat. Explosive Growth Projected in Next Five Years for RFID Tags. http://www.instat.com.

[15] Intel. Intel Sensor Nets/RFID Research Areas. Webpage. http://www.intel.com/research/exploratory /wireless_sensors.htm.

[16] S. H. Kim and P. Park. An efficient tree-based tag anti-collision protocol for RFID systems. *IEEE Communications Letters*, 11:449–451, 2007.

[17] S. H. Kim, M. K. Shin, and P. Park. A New Tree-based Tag Anti-collision Protocol for RFID Systems. In *Intl. Conf. on Communications in Computing*, pages 83–86, Las Vegas, USA, 2006.

[18] D. K. Klair, K.-W. Chin, and R. Raad. An Investigation into the Energy Efficiency of Pure and Slotted Aloha Based RFID Anti-Collision Protocols. In *In IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (IEEE WoWMoM'07)*, Helsinki, Finland, 2007.

[19] D. K. Klair, K.-W. Chin, and R. Raad. On the Accuracy of Tag Estimation Functions. In *In The 6th IEEE International Symposium on Communications and Information Technologies (IEEE ISCIT07)*. Sydney, Australia, 2007.

[20] D. K. Klair, K.-W. Chin, and R. Raad. On the Suitability of Framed Aloha Based RFID Anti-Collision Protocols for RFID-Enhanced WSNs. In *The 16th IEEE International Conference on Computer Communications and Networks (IEEE ICCCN'2007)*. Honolulu, Hawaii, USA, 2007.

[21] S. Lewis. Think RFID Technology. http://hosteddocs.ittoolbox.com/laran032604.pdf, 2004.

[22] X.-Y. Li, P.-J. Wan, and O. Frieder. Coverage in Wireless Ad-hoc Sensor Networks. *IEEE Transactions on Computers*, 52(6):753–763, 2003.

[23] J. Myung and W. Lee. Adaptive binary splitting: A RFID tag collision arbitration protocol for tag identification. In *2nd IEEE International Conference on Broadband Networks*, pages 347–355, Boston, MA, USA, 2005.

[24] J. Myung, W. Lee, and T. Shih. An Adaptive Memoryless Protocol for RFID Tag Collision Arbitration. *IEEE Transactions on Multimedia*, 8(5):1096–1101, 2006.

[25] NASA/JPL. Sensor Webs Project. http://sensorwebs.jpl.nasa.gov/.

[26] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan. The Cricket Location-Support System. In *ACM MOBICOM*, pages 176–184, Boston, MA, USA, 2000.

[27] N. B. Priyantha, A. K. Miu, H. Balakrishnan, and S. Teller. The Cricket Compass for Context-Aware Mobile Applications. In *ACM MOBICOM*, pages 1–14, Rome, Italy, 2001.

[28] RFID Journal. DOD Releases Final RFID Policy. http://www.rfidjournal.com/article/articleview/1080/1/1.

[29] RFID Journal. Wal-Mart Begins RFID Process Changes. http://www.rfidjournal.com/article/articleview/1385.

[30] M. Roberti. BP Leads the Way on Sensors. Webpage. http://www.rfidjournal.com/article/articleview/1216/1/2/.

[31] S. Shenker, S. Ratnasamy, B. Karp, R. Govindan, and D. Estrin. Data-centric storage in sensornets. *ACM SIGCOMM Computer Communications Review*, 33(1):137–142, 2003.

[32] D. H. Shih, P. L. Sun, D. C. Yen, and S. M. Huang. Taxonomy and Survey of RFID Anti-collision Protocols: Short Survey. *Elsevier Computer Communications*, 29(11):2150–2166, 2006.

[33] SkyeTek. Skyemodule M1-Mini. Datasheet. http://www.skyetek.com/Portals/0/SkyeModule_M1Mini_060426.pdf.

[34] H. Vogt. Multiple object identification with passive RFID tags. In *IEEE Intl. Conf. on Man and Cybernetics*, pages 6–13, Tunisia, 2002.

[35] J. Waldrop, D. W. Engels, and S. E. Sarma. Colorwave: An Anticollision Algorithm for the Reader Collision Problem. In *IEEE International Conference on Communications ICC*, pages 1206–1210, 2003.

[36] B. Zhen, M. Kobayashi, and M. Shimizu. Framed aloha for multiple RFID objects identification. *IEICE-Transactions on Communications*, E88-B:991–999, 2005.