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E^2MAC: An energy efficient MAC for RFID-enhanced wireless sensor networks

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ABSTRACT

The primary aim of any anti-collision protocols is to identify tags quickly, as doing so ensures that a Radio Frequency IDentification (RFID) reader incurs minimal energy wastage and achieves high identification rate. To date, researchers have proposed various protocols to minimize tag collisions and idle slots – key factors that determine a reader's read rate and energy expenditure. Most of these protocols, however, are designed for *single* reader systems. To this end, we propose E^2MAC, an energy efficient, distributed Medium Access Control (MAC) protocol for identifying and monitoring tags in RFID-enhanced wireless sensor networks. E^2MAC exploits the low power capability of a ultra-wideband transceiver and distinct pulses to address the reader collision problem. In addition, it uses ResMon, an enhanced dynamic frame slotted Aloha protocol to read and monitor tags. Lastly, E^2MAC uses a novel load balancing algorithm to amortize the cost of reading and monitoring tags to multiple readers. These E^2MAC features ensure that the contention level at each reader is kept at a minimum and distributed fairly. As a result, E^2MAC has a high reading rate and low energy consumption. In addition, E^2MAC helps in minimizing the impact of the tag orientation problem, where a tag becomes unreadable if its antenna is parallel to a reader's field lines. In particular, the use of multiple readers increases spatial diversity and hence increases the likelihood that a tag is readable by at least one reader. Our simulation results show E^2MAC to have very low energy consumption, reading delay and per-reader collision. More importantly, system designers have the flexibility to lower these metrics further with additional readers, bigger frame sizes, or by dividing tags into small groups.

1. Introduction

A recent development in the area of Wireless Sensor Networks (WSNs) is the coupling of a Radio Frequency IDentification (RFID) reader to a wireless sensor node to create RFID-enhanced WSNs—e.g., SkyeTek has developed a RFID reader [1] that mates with Crossbow's MICA2Dot sensor Motes [2]. Fig. 1 shows an example of RFID-enhanced WSN, where the tags shown can be attached to both animate and inanimate objects. Such networks can be deployed either indoors or outdoors, and is a marked departure from current RFID systems and WSNs that have thus far limited to sensing ambient elements such as temperature and humidity. Applications can range from tracking books in a library to smart homes. For example, in a smart home, RFID-enhanced nodes can be used to track tagged items in a home, thereby allowing users to manage their assets efficiently [3–5]. On the other hand, outdoor applications include disaster or habitat monitoring [6–8]. For example, in habitat monitoring, RFID-enhanced sensor nodes can be deployed on a farm to monitor tagged animals.

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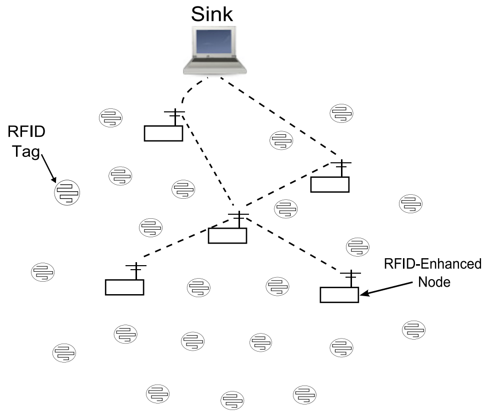

Fig. 1. RFID-enhanced wireless sensor network.

A number of organizations and researchers have started investigating RFID-enhanced WSNs. In [9], Ho et al. present an in-home elder health care system that is capable of monitoring the medication intakes of patients. In a similar work, Intel [10] has developed a system called "Caregiver's Assistant" to detect an elder's activities. Specifically, everyday household objects are fastened with an RFID tag so that they may be tracked when touched by an elder. In [11], NASA/JPL outlines a project called Sensor Webs. The goal is to develop a web of sensors for monitoring environment changes such as humidity, and take actions when events happen. Finally, BP Oil [12] is using RFID for location tracking and to sense the working condition of machines by monitoring their vibration.

Besides these projects, researchers have also investigated the energy efficiency of RFID systems; see [13]. These works show that an RFID reader consumes a significant amount of energy whilst scanning RFID tags. More importantly, existing anti-collision protocols are not energy efficient and lack tag monitoring capabilities. To this end, in our prior work [14], we proposed a novel tag reading protocol that allows a reader to read and monitor tags in an energy efficient manner. However, this work only considers a *single* reader. In fact, to the best of our knowledge, no works have considered both reading and monitoring of RFID tags using multiple readers.

Henceforth, this paper proposes E^2MAC, a multi-reader MAC that enables RFID-enhanced sensor nodes to cooperatively read and monitor a set of tags. In addition, E^2MAC employs a load balancing feature that segregates tags into small groups. As a result, each reader experiences fewer collisions as there is less contention between tags. For example, from our extensive simulation studies, in scenarios with 100 and 500 tags, each reader only observes on average fewer than 10 and 50 collisions respectively. Moreover, one can reduce collisions even further by adding more readers, using a bigger frame or by dividing tags into smaller groups. Apart from that, E^2MAC is significantly more energy efficient than other Framed Slotted Aloha (FSA) protocols during identification and monitoring. Moreover, it makes novel use of Ultra-Wideband (UWB) to solve the reader interference problem efficiently. These key design features, therefore, make E^2MAC ideal for use in resource constrained wireless sensor networks. Lastly, the use of multiple readers has the added benefit of spatial diversity, which helps in increasing the likelihood of reading tags that are impeded by the tag orientation problem.

The remainder of this paper is structured as follows. Section 2 discusses three key problems addressed by E^2MAC. After that, in Section 3, we discuss prior works that address some of these problems. Section 4 outlines E^2MAC, specifically, the key features that address the problems outlined in Section 2. This is then followed by our simulation methodology in Section 5, where we evaluate E^2MAC in single and multi-reader scenarios. Section 6 presents the performance of E^2MAC in terms of collisions, idle times and identification delays. Section 7 presents our conclusions.

2. The problems

The aim of E^2MAC is to amortize the cost of reading and monitoring tags amongst multiple RFID-enhanced sensor nodes. Our conjecture is that by employing multiple readers, there will be fewer collisions and better energy efficiency as multiple readers are able to share the workload of reading tags. Apart from that, multiple readers may help in overcoming the tag orientation problem, where a tag becomes unreadable if its antenna is parallel to a reader's field lines. Hence, with multiple readers, a tag has a higher probability of being identified by at least one reader, each of which with different orientation and coverage.

The use of multiple readers, however, gives rise to the following problems: (i) reader interference, (ii) tag collision, (iii) reader overload, and (iv) energy constraint.

Problem (i) occurs when multiple readers with overlapping interrogation zone attempt to read tags simultaneously. In Fig. 2(a), we see that a tag is within the interrogation zone of both R1 and R2. Hence, when both readers start reading, the tag is unable to decode commands from either reader. This problem is similar to the hidden terminal problem in wireless networks. The key difference, however, is that tags are unable to sense the channel nor response with a message, e.g., clear-to-send, to inform the readers that it is busy receiving. Conversely, readers with overlapping interrogation zone may interfere