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RFID Range Extension with Low-power Wireless Edge Devices

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***Abstract*—Coverage area is an important performance metric for RFID systems, especially those used for inventory management. As such, there are a range of methods being developed to try to increase the coverage area of RFID systems without requiring additional costly and power hungry RFID readers. Most existing approaches to increase coverage employ RFID readers with multiple antennas, but this creates problems in deployment and in the timing of the RFID tag reads from the different antennas. In this paper, we propose a different approach to extend the coverage area of a single reader, using a ZigBee-based, battery-operated device we call an *edge device* to cooperate with the RFID reader on reading the RFID tags. The edge device is also compatible with existing RFID range extension methods for additional increase in coverage. We implement an edge device hardware platform and evaluate the performance of the system in terms of coverage extension, and we provide estimates of the lifetime achievable for different tag access scenarios. Our experiments show that each low cost, easily deployable edge device can increase the coverage area by about 70%, and that they last for about 1.5 months if the tags are accessed twice an hour to upwards of 4 years if they are accessed once a day, as is sufficient for many inventory management applications.**

***Index Terms*—Passive RFID, Range extension, ZigBee.**

I. INTRODUCTION

Radio-frequency identification (RFID) systems use RF electromagnetic fields to communicate with tags for the purpose of identification. RFID systems are widely used for managing assets and people, as well as for tracking inventory by attaching tags to merchandise. RFID systems are generally composed of RFID tags, which store the ID information, and an RFID reader, which transmits the electromagnetic energy to power the tags as well as to access or modify the tag ID information. There are three types of RFID tags: passive tags, active tags and battery-assisted passive tags. Among these three types of RFID tags, passive RFID tags have the advantage of small size and low cost, and they have close to zero maintenance. Because of these advantages, passive RFID systems have been rapidly developed in recent years. In particular, passive ultra-high frequency (UHF) RFID readers and tags communicate in the frequency band from 860 MHz to 960 MHz, where the tags communicate by backscattering the radio waves they receive from RFID readers. UHF RFID systems have a reasonable access range while at the same time supporting tags that cost less than $0.10. Thus, UHF RFID systems are currently being used in a wide range of applications.

The maximum range of tag access (i.e., the read range) is a very important metric for RFID systems, representing the coverage capability for the RFID system [1]. A system with a long tag access range can cover more area for tag reads (e.g., for inventory tracking), and thus can track more assets with fewer RFID readers and can provide more alerts in an access control system.

There are several different features of an RFID system that affect the maximum access range. First, the transmit power of the RFID reader determines the amount of energy that can be harvested by the tag. However, The Federal Communications Commission (FCC), in part 15 of its regulations, limits the transmit power in the UHF frequency band to 1 W. A typical UHF RFID reader is likely to transmit power up to the legal limit. Second, the gain of the antenna also affects the maximum access range. Different antenna can be used in different applications, leading to various access ranges. Finally, different types of tags attached to different objects will lead to different maximum access ranges. For example, an NXP HANA RFID tag [2] being accessed by an Impinj Speedway UHF RFID reader [3] can achieve a 3 m access range, while an Omni-ID Ultra tag [4] with the same reader can achieve close to a 30 m access range (based on our experiments).

Thus, with the reader using the full 1 W transmit power, a specific RFID antenna, and a specific tag attached to an object, the access range of each system can be determined. However, the area covered by this access range may not be sufficient for the application. In order to fulfill the requirements of the application, one solution is to increase the number of antennas of each reader. However, as the multiple antennas are all wired to the reader, this makes deployment difficult and messy, with wires needing to be strung in the area of deployment. Another solution is to utilize multiple readers working cooperatively for covering the area that is required for the application. However, this will dramatically increase the cost of the system (as readers can range from $500 to $1500). Moreover, since most RFID readers are wall powered, this also makes deployment difficult, as the readers must be placed near existing outlets or extension cords must be provided.

Given these current limitations for RFID access range, in this paper we propose a system that consists of multiple

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ZigBee-based, battery-powered, low-power readers, which we call *edge devices*, that cooperate with the main reader which we call *base station* to achieve range extension. Since the edge devices are battery powered and communicate with the base station using ZigBee [5], no wires are needed, which enables an easy and fast deployment of this RFID system with range extension. This system is scalable, and given that the cost of this edge device is lower than a typical RFID reader[2], this approach will cost less than using multiple readers.

The rest of this paper is organized as follows. In Section II, a survey of the related work in this area is presented. The description of our proposed RFID system with range extension is provided in Section III. Section IV describes the hardware design of the edge devices. Section V presents results from physical experiments using our system, and conclusions are drawn in Section VI.

II. RELATED WORK

Several methods have been developed to achieve range extension beyond what is possible with a single RFID reader. These methods can be broadly divided into two categories: 1) increasing the number of antennas, and 2) increasing the number of readers. These two approaches can both achieve access range increases with some cost.

The CS468 16-Port RFID Reader [6] is one example of a reader that achieves range extension using multiple antennas. This RFID reader can support up to 16 antennas. Each antenna can cover the same area within its access range. Thus, this system can achieve high overall area coverage. One problem for this system is the difficulty in deployment. Deploying 16 antennas with coaxial cables is not easy in an inventory management scenario. Furthermore, although the attenuation of the coaxial cable is low, the signal and power lost through long distance power transmit in the coaxial cable is not negligible. Scalability is another problem, as the antenna port designed on an RFID reader limits the maximum area the system can cover. Other range extension solutions through increasing the number of antennas [7], [8], [9] also have similar limitations in terms of latency, difficulty in deployment and poor scalability.

Bellantoni proposed a ZigBee-Enabled RFID Reader Network [10]. The idea of this work is to attach a ZigBee module to a standard RFID reader so that it can communicate with a control computer directly. The design can build a self-sufficient, battery powered Distributed Autonomous Reader Network (DARN) that can achieve flexiblility in the deployment of the RFID reader. However, this work mainly focuses on building a ZigBee based network rather than increasing the RFID access range. Furthermore, this work does not provide any evaluation of the system, so we cannot determine the performance of their proposed system. Neither RFID range nor system lifetime are analyzed, and use of multiple readers will increase the system cost dramatically. Finally, there is some work that focuses on the collisions when multiple readers work cooperatively [11], but this work simply identifies the appropriate distance to place different readers from each other.

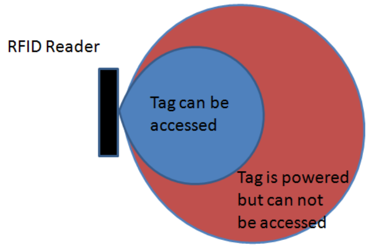

Fig. 1. Access area and power area for a standard RFID reader. A much larger area can be powered from the RFID reader than can be accessed by the reader.

III. SYSTEM DESIGN

The goals of our RFID range extension system are to increase the coverage area of an RFID reader with low cost in terms of the equipment, easy deployment without wired connections, and the ability to scale as additional coverage is needed. Additionally, we want our system to be compatible with existing UHF Class 1 Generation 2 (C1G2) [12] RFID systems so that the edge device can access low cost, comercially-available UHF RFID tags. We meet these goals by employing a ZigBee-based, wireless, low-power *edge device* the cooperates with the reader to access the tags.

According to the C1G2 protocol, the RFID reader communicates with an RFID tag through the following steps:

- The reader continuously emits an RF carrier signal and listens for tag replies.
- Tags in the communication range of the reader modulate the energy emitted by the reader to send the tag information back to the reader.
- The reader demodulates the received signal and obtains the tag information.

For a standard RFID system, there are two cases where an RFID reader cannot access a tag. First, the tag is not powered, which means the power captured by the tag is not sufficient to transmit the tag information back to the reader. If a tag is not powered, there is no way for this tag to be accessed by the reader. Second, the RFID tag is powered, but the information sent from the tag to the reader is not received by the reader. The reason for this is that the sensitivity of the RFID reader is not high enough to decode the signal received by the reader. Fig. 1 shows the difference between the area where the tag is accessible and the area where the tag is powered. The idea of our system is to access those tags in the "powered but not accessible" area with an edge device with very low transmit power and high receive sensitivity.

The edge device we designed is composed of a ZigBee module to send the tag information back to the base station, a microcontroller (MCU) that controls the RFID C1G2 protocol and coordinates with the ZigBee module, an RFID reader chip that modulates the command and demodulates the received signal replies from the tag, and a battery pack. At the base

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[2] Edge devices are targeted at a price of $100 to $250, as they do not require the entire set of reader functions.

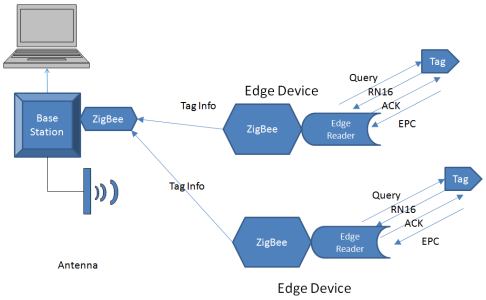

Fig. 2. RFID system with range extension using two edge devices.

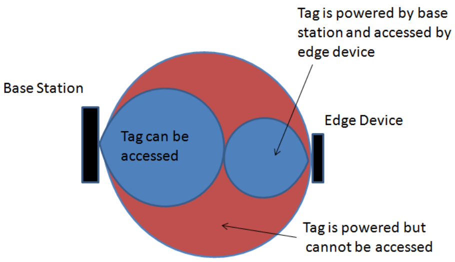

Fig. 3. Access area and power area for a standard RFID reader cooperating with one edge device.

station side, a ZigBee module is connected to the base station to collect the data received by each edge device. Fig. 2 shows the design of our RFID system with range extension using two edge devices.

When an edge device cooperates with the base station, the edge device is deployed at the edge of the access range of the base station in order to obtain the maximum range extension. For tags that are located in the access area of the base station, the tag will be accessed directly by the base station, while for those tags that are located out of the access area of base station, these tags are accessed by the edge device. When the tag information is collected by the edge device, it is sent to the base station via the ZigBee channel. Fig. 3 shows the resulting access area when an edge device cooperates with the main RFID reader.

In order to provide additional coverage area, multiple edge devices can be deployed. Fig. 4 illustrates the coverage area for an RFID reader cooperating with two edge devices to increase coverage. Additionally, edge devices can also be used with any of the existing range extension methods listed in Section II to obtain a hybrid system and achieve increased coverage.

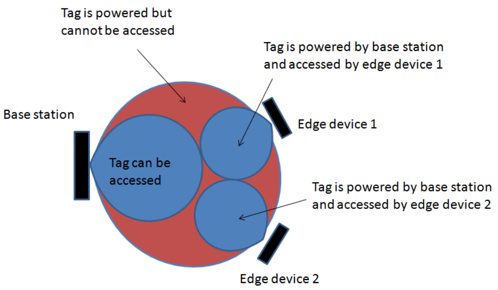

Fig. 4. Access area and power area for a standard RFID reader cooperating with multiple edge devices.

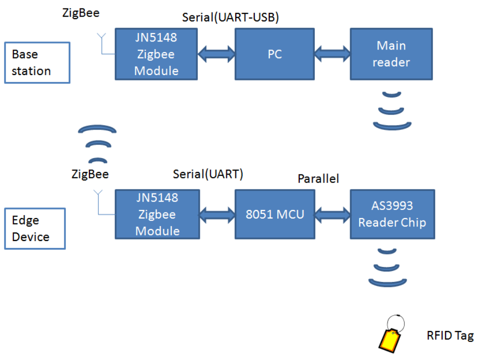

Fig. 5. Architecture of our edge device implementation.

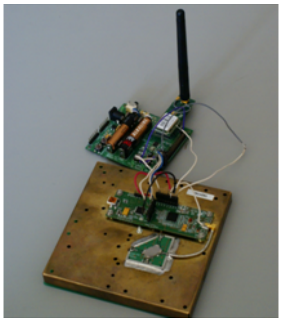

Fig. 6. Edge device implementation.

IV. HARDWARE IMPLEMENTATION OF EDGE DEVICE

The edge device we implemented is composed of a Silicon Laboratories C8051 [13] as a control MCU to coordinate all ZigBee and RFID communication; a reader chip, Austria Microsystems AS3992 [14] RFID reader, to control the physical RFID reads; and a Jennic JN5148 [15] ZigBee communication module. Also, we connect a JN5148 to the base station in order to receive the tag information sent by the edge device via the ZigBee channel. Fig. 5 shows the system architecture, and Fig. 6 is a picture of the actual hardware we implemented.

In order to determine expected lifetime of the system, we calculate the power consumption of different states of the edge device, as shown in Table I. State “RFID Active” is the state when the edge device is sending or receiving an RFID signal;

TABLE I
POWER CONSUMPTION (mW)

	Sleep	RFID Active	ZigBee Active	RFID Active with ZigBee
Power	0.015	636	142	778

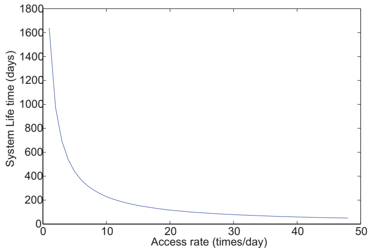

Fig. 7. Lifetime of the edge device as the number of accesses per day increases.

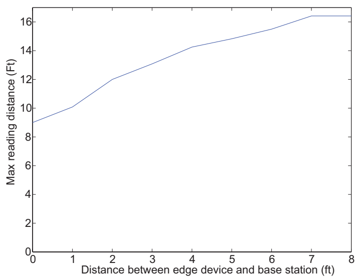

Fig. 8. Maximum access distance as the distance between the base station and the edge device increases.

state “ZigBee Active” is the state when the Jennic JN5148 is active but the reader chip is sleeping; state “RFID Active with ZigBee” is the state when the edge device is communicating through both the RFID channel and the ZigBee channel; and state “Sleep” is the state when all of the components of the edge device are in their sleep modes.

Using these power values, and assuming that the edge device is powered by 4 AA batteries, each of which can provide 2200 mAh, we can determine the expected lifetime for our system. In particular, here we look at an inventory tracking scenario that requires the inventory to be accessed a small number of times every day. We assume that during each access, the edge device queries the tags in its area for 30 s in order to ensure that all tags are accessed. Also, the ZigBee module needs to wake up for 10 s once every hour to handshake with the base station, keeping the ZigBee connection alive. Using these values, Fig. 7 shows the simulation results for the system lifetime of the edge device as we vary the number of accesses per day. From these results, we can see that if the system accesses tags once every day, the edge device can work for as long as 4 years. If the reader accesses tags every half hour, the edge device is still able to work for 1.5 months.

V. EXPERIMENTAL RESULTS

We performed several experiments to evaluate the performance of our RFID system with range extension using edge devices. In the first experiment, the antenna of the base station is fixed, and we place the edge device very close to the base station with the edge device antenna pointed in the same direction as the base station antenna. We place tags at different distances from the base station to evaluate the maximum distance for tag access. Both the edge device and the base station as well as the tag are placed 25 cm from the ground. We repeat this experiment as we move the edge device away from the base station.

Fig. 8 shows the experimental results for the maximum distance the tag can be placed from the base station and still be accessed by the system. Without using our system, a single RFID reader can achieve only an 8 ft. access range, while our experimental results in Fig. 8 show that using the edge device, the maximum access range is increased to 16.5 ft., when the edge device is 8 ft. from the base station. If we place the edge device at a distance of more than 8 ft. from the base station, there is an area that neither the base station nor the edge device can access. Furthermore, the maximum access distance we can achieve is 16.5 ft. no matter where the edge device is placed. The reason for this limitation is the power harvested from the base station can only support those tags that are located within 16.5 ft. of the base station.

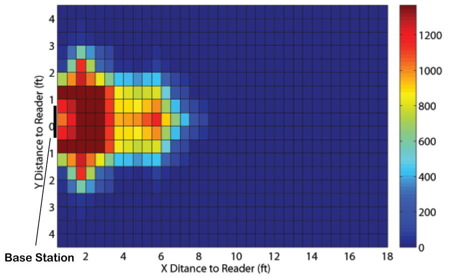

Fig. 9. Base station coverage. Results show tag access rate in tags/min.

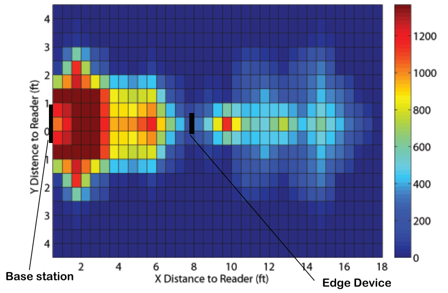

Fig. 10. Coverage when there is one edge device with antenna pointed in the same direction as the base station antenna. Results show tag access rate in tags/min.

In the second set of experiments, we fix both the base station and the edge device and evaluate the coverage area. We use tag rate as the performance metric, where tag rate is defined as the average number of tags that the reader as well as the edge device can access in 1 minute. The coverage result is shown in a 2-dimensional image, and both the edge device and the base station as well as the tag are placed 25 cm from the ground. If neither the base station nor the edge device access the tag in 1 minute, we assume that the tag is located in an area with no coverage.

First, we evaluate the coverage of the base station without any edge devices as a baseline for coverage, as shown in Fig. 9. Next, we place the edge device 8 ft. away from the base station. Both the base station and the edge device aim their antennas in the same direction. Fig. 10 shows the tag access rate for this scenario. Comparing Fig. 9 and Fig. 10, the additional area of coverage is the result of adding the edge device. The tags located far away from the base station have less harvested power. This is the reason the tag rate in the area that is covered by the edge device is lower than that in the area covered by the base station. With such a low power wireless edge device, we obtain a 70% increase in coverage area compared with just using the base station reader.

Fig. 11 shows the coverage results in tag rate when the base station and the edge device have their antennas pointed

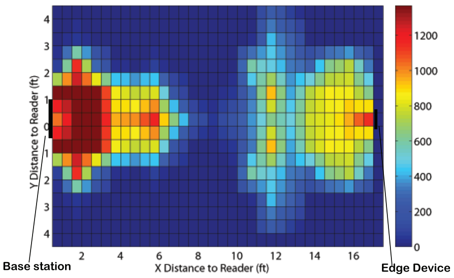

Fig. 11. Coverage when there is one edge device with antenna pointed in the opposite direction as the base station antenna. Results show tag access rate in tags/min.

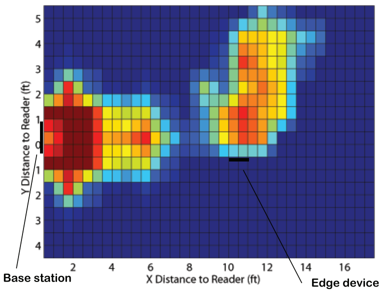

Fig. 12. Coverage when there is one edge device with antenna pointed in the vertical direction. Results show tag access rate in tags/min.

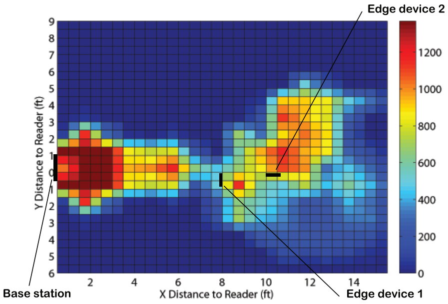

Fig. 13. Coverage when there are two edge devices with antenna pointed in the same direction as the base station antenna and in the vertical direction. Results show tag access rate in tags/min.

in opposite directions. The distance between the two antennas is 16.5 ft. in order to achieve maximum access distance. Unlike the last experiment, this placement of the edge device will not block any electromagnetic waves sent by the base station. The results show that the coverage area is even better than the previous experiment's results, providing approximately 90% increase in coverage area compared with just using the base station reader. However, this deployment of the edge device leads to relatively low tag rate when the tag is located 8-10 ft. from the base station, which may be an issue in real inventory management scenarios.

Fig. 12 shows the coverage results when the edge device is 10 ft. from the base station and pointed in the vertical direction. It is easy to see that we get better coverage in the vertical direction due to the direction of the edge device, with the coverage area increasing by approximately 70% compared with just using the base station reader.

Finally, we tested the scenario when the base station cooperates with two edge devices in order to further increase coverage. Fig. 13 shows the results from this experiment, with one edge device placed 10 ft. from the base station and pointing in the vertical direction and a second edge device located 8 ft. from the base station and pointing in the same direction as the base station. These two edge devices work together to obtain coverage extension. The results show that the coverage increases dramatically with multiple edge devices, increasing coverage by approximately 160% compared with just using the base station reader, showing that if we place more edge devices into the system, it is possible to obtain even better coverage.

VI. CONCLUSIONS

In this paper, we proposed an edge device that can cooperate with an RFID reader to extend the access range for RFID tags, hence increasing system coverage. This edge device has the advantage of low power operation, being easy to deploy and enabling a highly scalable system. We implemented the edge device and evaluated the performance of the system with an existing RFID reader and RFID tags. The results show that the edge device can improve the coverage and access range performance of existing RFID systems. When an RFID reader cooperates with two edge devices, the system is able to cover approximately twice the area compared to the coverage area when a single edge device is used. Also, the edge devices can work with existing range extension methods such as a multiple antenna system to create a hybrid system and obtain even more coverage.

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