On the Potential of Sensor-Enhanced Active RFIDs

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Abstract

As the popularity of the passive RFID technology continue to surge, we see promising applications in its active counter-genre. There is however an inherently limited lifetime in any active RFID-based system because the active RFID tags operate on batteries. To hurdle through the energy limitation, we think the opportunities lie in the creative embedding and use of sensors with the active RFID tags.

With a case study, referred to as the personal object alarm, we show the potential of embedding sensors to active RFID tags for optimal system lifetime and accuracy. In particular, from the range estimation sensor, we derive the relative distance and velocity of the active RFID tags on the user and object. In turn, out-of-proximity alert can be generated timely when the user's personal object moves out of the pre-defined range. Our experiments show that with sensor-enhanced active RFID system lasts twice as long while the accuracy of the alert is improved by 47%, in comparison to a system without any embedded sensors.

1. Introduction

We have witnessed Wal-Mart's determination in fully RFID-tizing its supply chain operation. As the popularity of the passive RFID technology continue to rise, we see promising applications in its active counter-genre. Asset tracking is one such example where unauthorized removal of expensive equipment can only be detected reliably by the longer-range active RFIDs. The major drawback to practical, widespread use of active RFIDs is at the power requirement. Unlike the passive RFID tags, the active ones run on batteries. There is an inherently limited lifetime in any active RFID-based system. To be able to leap through the energy limitation hurdle, we see research and development opportunities in optimizing the energy efficiency in the system design and we think the hope lies in the creative use of sensors in conjunctin with the active RFID tags.

In short-range radio frequency systems, the energy requirement is proportional to $range^4$ [1]. This suggests that relative to computation, radio communication is the primary consumer of energy. Active RFID-based systems may easily drain the battery if the communication component is not designed with caution. One major rule of thumb is to avoid as much unnecessary radio communication as possible. We think information derived from additional sensors can help.

Our premise is to show in a practical everyday application the benefit of this *sensor-enhanced* approach towards energy efficient system design. The application idea arises from a frequently observed problem - noticing the cellular phone is left behind only when we need to make a call on the run. We refer to the system which alerts the user of the personal objects going out of proximity as the *personal object alarm*.

The basic mechanism is to tag the personal object and the user with the range-sensor-embedded active RFIDs When the estimated distance is greater than a pre-defined range, the tag on the user alert the user. In addition to cellular phones, other objects that one might need to keep a close eye on include (in)valuable assets such as wallets, key chains, pets, and children. The personal object alarm can be generalized to keep restricted objects within a confined area as well, for example, unpaid merchandizes in a store, expensive equipments in a laboratory, serious mental patients in a recovery facility.

If the RFID tags exchange the range information at a high frequency, the out-of-range detection sensitivity will be higher, but the battery might drain quickly. On the contrary, if the exchange is in a low frequency, the risk is that the system might detect the personal object going out of reach too late. Taking the sensor-enhanced approach, we adapt the range information exchange frequency based on *the distance and relative moving speed between the user and the object*. The intuition is that when the user and the personal object are close or relatively steady to each other, the rate of the range information exchange can be low to conserve energy. When the two entities are apart around

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the critical range or moving relatively fast to each other, the transmission rate is set high for timely detection of the out-of-range events.

We evaluate the energy efficiency and the out-of-range detection accuracy of the system applying various degrees of mobility to the user and the object. The experimental results show that the detection accuracy is improved by 47% while the transmission overhead, i.e., the energy consumption, is reduced by 56%.

2. Personal Object Alarm System

The personal object alarm system serves as a reminder to ensure the personal object is with a pre-defined range to the user. The personal objects to be tracked are tagged with the special hardware in small form factor that consists a simple processing unit and a short-range wireless radio. The person who wishes to track the important objects of his/hers would also wear such a special hardware. If the personal object lies within the safe range, it will be identified as in-range. When the personal object goes out of the range, it will be identified as out-of-range and the system will remind the user of the out-of-range event. The detection accuracy and energy efficiency depend on how frequent the radio signals are sent from the object and the range estimated at the user. We detail in the subsequent subsections the basic periodic mode and the sensor-enhanced mode of the detection mechanism.

2.1. Periodic mode

In periodic mode, the personal object node transmits signals with a constant time interval. When the user node receives the signal, it estimates the distance to the personal object node from the received signal strength indication (RSSI) of the signal and check if the estimated distance is larger than the safe range. If it is larger than the pre-defined range, it triggers an alarm to the user. Losses of signals may seriously compromise the sensitivity of the alarms. A timer is added to ensure that the user node will not be waiting until it is too late to detect the personal object moving out of range. This timer expires to trigger an alarm if no signals from the personal object side are received after the timeout interval. Whenever the user node receives a significant signal, the timer is refreshed.

Overall, the periodic mode contains two components. One is to check the distance from the probing message, and the other is to set a timeout interval to prevent slow detection due to the losses of range estimation signals. The accuracy of this mechanism will depend on the object probing rate and the person's timeout interval. One must manually adjust the probing rate to meet the system's specific needs in different situations.

2.2. Sensor-enhanced mode

In the sensor-enhanced mode, the system adapts the signal transmission rate based on relative distance and velocity. To enable the estimation of relative velocity, the signal transmission protocol is extended to include feedback from the user node to the personal object node.

The user node not only estimates the distance to the personal object node, but also sends actively back to the object node the estimated distance (d_p) and the timestamp (t_p) taken at the moment the signal is received. In turn, the object node can estimate the relative distance to the user node from the feedback radio transmission. The object node transmits again the relative distance (d_o) estimated and the timestamp (t_o) at which the feedback signal is received. The relative velocity (v) is calculated at each node by the difference in between the two distance measurements to the difference in time as follows:

$$v = (d_p - d_o)/(t_p - t_o) \tag{1}$$

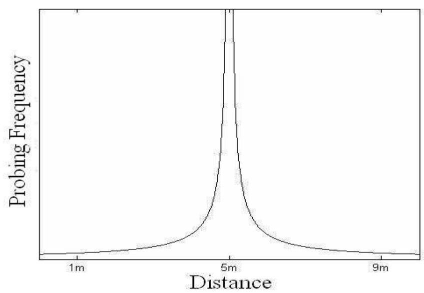
Next, we define how the rate of signal transmission is adjusted based on the estimated distance and relative velocity. Our design principle is (1) to project the time the two nodes will move out of the range and (2) to tune the transmission interval such that there are a fixed amount of signals sent before the nodes are out of range. This allows more recent distance and relative velocity measurements and in the meantime tolerates a small number of signal losses. The user node continues to update the projected out-of-range time (T_o) as formulated in Equation (2). This is also the timeout value for the system to alarm the user in case that all the subsequent signals are lost.

$$T_o = (R - d_o)/v \tag{2}$$

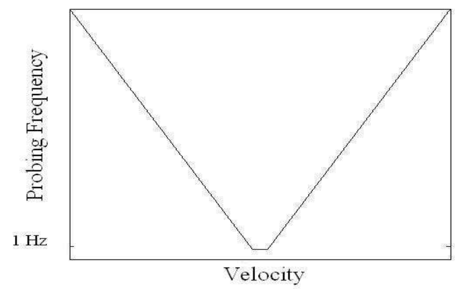
The object node sets the transmission interval (T_p) to a fraction of (T_o). The parameter K is introduced to represent the fraction as formulated in Equation (3). The value of K ranges from 0 to 1. When the value of K is set large, the object nodes sends a small number of signals before the timeout which might result in a lower accuracy out-of-range detection. However, if the value of K is set small, the detection sensitivity will be high but the communication overhead will be relatively higher.

$$T_p = K \times (R - d_p)/v \tag{3}$$

One exception to handle is when the relative velocity equals zero. It might appear that the relatively static nodes are less at risk moving out of the safe range, but we find the system predictability being very low every time the nodes begin to move. We thus set use the average relative velocity to calculate (T_p) and (T_o) when the relative velocity is



(a) Distance vs. Probing frequency
While the relative distance of nodes is closer to the target range, the probing frequency will be tuned higher.



(b) Velocity vs. Probing frequency
The probing frequency will be tuned higher according to the value of relative velocity regardless of the direction.

Figure 1. Probing frequency in the sensor-enhanced mechanism

zero. Figure 1 illustrates the relationship between the transmission frequency, the inverse of the transmission interval, to the distance and relative velocity. Figure 1(a) shows that the frequency is set high when the distance is close to the target range and Figure 1(b) shows that the frequency goes high when the relative velocity increases, no matter whether the two nodes are approaching or moving away from each other.

To prevent two nodes moving away from the range without any signal transmitted, we further bound the maximum value of the transmission interval (T_p). This upper bound (T_u) is determined as the time it takes for a user to move away from the object with the fastest possible speed (V_{max}). This is the shortest possible time that a user can move away from the object and the transmission interval should not be longer than this. Otherwise, the two nodes might move out of the range without any attempt estimating the distance and relative velocity.

$$T_u = R/V_{max} \quad (4)$$

3. Evaluation

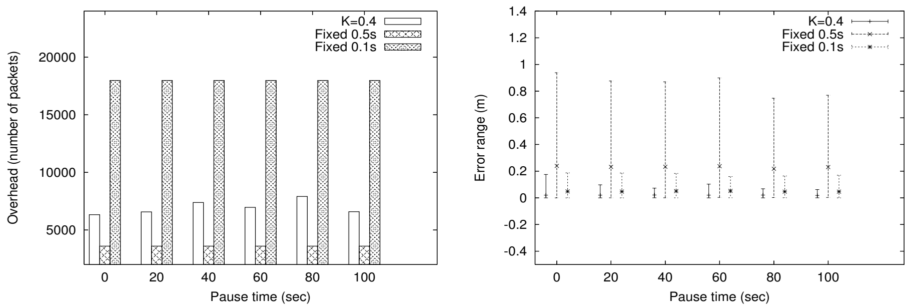
The objective of the evaluation is to demonstrate quantitatively the benefit of sensing information to system communication, in particular, how much the accuracy and energy efficiency can be improved adapting the range detection mechanism based on the relative distance and velocity. We implement both the periodic and sensor-enhanced detection mechanisms as described in Section 2 under random user and personal object mobility and discuss in this section the performance improvement of the sensor-enhanced mechanism relative to the basic periodic version.

3.1. Methodology

We implement the sensor-enhanced personal object alarm in the network simulator version 2, i.e., *ns-2* [2]. *ns-2* is a packet-level discrete event simulator for wired and wireless data network simulations. The user and personal object system is simulated by a simple 2-wireless-node scenario. The radio range is set to 20 meters while the area of experiment is set to 15x15 square meters to ensure that the two nodes will be reachable to each other throughout the simulations. The target detection range for the alarm is set to 5 meters.

To simulate the movement of nodes, we adopt the random waypoint mobility model [3]. In this model, nodes move with random speeds towards random destinations. A different pause time between two consecutive movements is set to represent a different degree of mobility. A lower pause time implies a higher overall mobility, i.e., a higher average speed and a higher frequency of changing directions. We think the mobility model is reasonable given the everyday behavior of human migration. We tend to move from one place to another, stop and handle issues for a while, and then move on. In our simulations, the speed of each movement is chosen uniform randomly from 0.3 to 2 meters per second, which is also around the speed range of human walking. We vary the pause time interval from 0 to 100 seconds. For each pause time, random moving speeds and destinations are generated to run an 8-hour simulation The intention is to cover the 9 to 5 working hours.

The performance metrics are detection accuracy and communication overhead. The user would prefer timely alert when the important personal object just drops out of the alarming range. In the meantime, the user would also prefer not to be bothered if the personal object is not re-



(a) Overhead

(b) Error

Figure 2. Comparison of the periodic and sensor-enhanced mechanisms

ally moving out of reach. Thus, the detection accuracy is defined as the distance between the personal object and the 5-meter radius sphere centered at the user when the out-of-range event is detected. Detection accuracy is a strong indicator of the system practicality.

We are not able to measure the energy consumption from the simulations. Instead, we measure the communication overhead. That is the amount of radio signals transmitted throughout the simulation. Given that the wireless radio is the primary energy consumer, the communication overhead is a strong indicator of the system energy consumption.

The detection error derived from the simulations is a result of delay in communication, not the error from the range estimation. The range in the simulation is derived from the RSSI and the known propagation model implemented in the simulator. This is saying that the range estimations in our experiments are virtually perfect. In the actual environment, the accuracy of the range estimation depends on the hardware, the estimation techniques used, and the physical environment. And the accuracy of the range estimation mechanisms may affect the detection accuracy of the personal object alarm. We are yet to evaluate the effect of different range estimation mechanisms to the system and this will be addressed in more detail in the future work section.

3.2. Performance Comparison

Lastly, we compare the sensor-enhanced mechanism to the basic periodic version that transmits radio signals at a constant rate. The time intervals for the periodic transmissions are set to 500 and 100 milliseconds. The amount of communication overhead for the periodic version is proportional to the transmission time interval. The 500 and 100 millisecond cases are chosen to represent the two extremes in terms of communication overhead.

Figure 2(a) shows that the sensor-enhanced version (k=0.4) performs well relative to the periodic one. With low transmitting frequency (500 ms, Fixed 0.5s), the amount of overhead is very small. The amount of communication overhead is 5 times as high with a higher transmitting frequency (100 ms, Fixed 0.1s). As for the sensor-enhanced mechanism, the communication overhead required is in between the two periodic cases.

The results of the error range analysis are depicted in Figure 2(b). The error range is the maximal and minimal error throughout the 8 hours simulated time, the average error is also plotted for reference. Figure 2(b) shows that the sensor-enhanced mechanism (k=0.4) performs better not only in terms of the average error, but also in the error range bound, except in the 0 pause time case.

4. Conclusion

To leap through the hurdle of energy limitation, we think the next generation RFID development and commercial opportunities lie in the creative use of sensors on the active RFID tags. With this case study, we show the potential of embedding sensors to active RFID tags for optimal system lifetime and accuracy. In particular, from the range estimation sensor, we derive the relative distance and velocity of the active RFID tags on the user and object. In turn, the out-of-proximity alert can be generated with high accuracy while the system lifetime is doubled.

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