Low power and agile sensor data retrieval using dual interface passive RF tag

Kenichi Sugimoto, Jin Mitsugi, Osamu Nakamura and Jun Murai
Auto-ID Lab. Japan, Keio University, Fujisawa-shi, Japan 252–8520
{mel, mitsugi, osamu, jun}@sfc.wide.ad.jp

Abstract—Consider a situation where one desires to retrieve sensor data from an arbitrary environment via a moving interrogator. Maintenance of street lights and electric apparatus in conduits for example. The fundamental problems with this system have been 1)the trade-off relation between power consumption by sensor and the data retrieval rate for the interrogator, and 2) the data retrieval agility for the moving interrogator. A higher duty ratio incurs more power consumption in sensors whereas a lower duty ratio leads to a less reliable retrieval rate. Even though there have been such efforts as adaptive sleep period control which was derived from the packet arrival rate, they didn’t systematically solve the problem, particularly for moving-interrogator environment. This paper presents a solution of separating the timing of sensor-sampling and the timing of sensor-data retrieval. The asynchronous data retrieval mechanism is facilitated by a dual interfaced UHF passive RF tag known as a “recorder tag” which the authors have been developing. This paper examines the power consumption composition of a prototype recorder tag. The power consumption efficiency of the proposed data-retrieval method is discussed in comparison with that of the existing method in terms of “Sensor Sampling Interval vs. Battery Life Expectancy.” The authors also evaluated the viability of retrieving sensor data through a moving-interrogator. We specifically inspected the relationship of “Interrogator’s Moving Speed vs Successful Data Retrieval Rate.” The tests showed that with a commercial 1.2V rechargeable battery, the recorder tag lasts for 21 days for luminance and temperature sensing using a 30 minute sampling interval, extending the traditional battery lifespan ten times longer, yet still preserving 100% time availability for sensor data retrieval. The power consumption is expected to be eight times as efficient when using optimized circuitry. Experiments in an emulated fading environment reveal that the data retrieval rate is observed to be the highest when the maximum relative speed between the moving-interrogator and the recorder tag is less than 3km/h, with an optimized distance of separation being 10cm for a 27dBm EIRP interrogator. The moving speed, 3km/h, can be improved by optimizing the anti-collision procedure and by enhancing the sensitivity of the recorder tag.

I. INTRODUCTION

Consider a situation where one is to retrieve sensor data from an arbitrary environment via a moving-interrogator. There exists a certain necessity for such a procedure in many real world applications.

1) Monitoring the status of street lights: Currently, the authors are proposing and attempting to substantiate a sensor system where they can monitor the status of street lights on highway. Attached to each street light is a sensor that measures a light brightness at a particular interval during the night. The sensor accumulates data on its chip memory. The data of street lights are retrieved by a passing car equipped with an interrogator that wirelessly communicates with each sensor (Fig. 1). Processing the data, specifically looking for the light with low brightness, allows for the detection of lights that have gone dead and need to be replaced.

2) Conduit Maintenance: This example utilizes sensor data for conduit maintenance. Yoshioka et al[1] have worked on the wireless retrieval of data through a manhole from the sensor that is placed beneath the lid. They have theoretically computed the “data retrievable” distance by calculating “power loss through lid-penetration” based on such parameters as the tag-antenna gain, tag transmission power level, reader antenna gain and reader reception level on 426 MHz.

There are two major problems with the system of retrieving sensor data from an arbitrary environment via a moving-interrogator: Power Consumption and Interrogation Speed.

1) Power Consumption: The system suffers a trade-off relation between power consumption by the sensor and the data retrieval rate for the interrogator. A higher duty ratio in receiving mode incurs more power consumption whereas a lower duty ratio leads to a less reliable retrieval rate. Even though there have been such efforts as “adaptive sleep period control” derived from packet arrival rate [2]-[4], they didn’t systematically solve the trade-off problem, particularly for moving interrogator environment. The use of sensor-enabled passive RF tags is the alternative approach to accomplishing low power and agile sensor data retrieval [5], [6]. But in this case, sensor data is only available at the instance of...
empowerment by the interrogator. The data accumulation in the passive RFID tag requires other mechanism such as battery assisted passive (BAP) tag. The type of embedded sensor is prefixed and therefore cannot be changed upon user’s requests. Philipose [7] presents an architecture in which a low-power MPU furnished with a passive RFID air protocol is empowered by the radio signal from a passive RFID interrogator. This way, we can use sensors based on the user requirement, still also keeping the availability of instantaneous sensor data.

2) Data Retrieval Speed for Moving-Interrogator: The system requires an interrogator with a fast read-speed as there is only a limited time in which the interrogator physically stays in tag-readable range. The faster the interrogator is moving, usually the less time it has for reading tags. The influence of moving speed might be relevant when we need to retrieve a large amount of data from a sensor tag.

The remainder of this paper is organized as follows. Section II introduces Dual Interface Passive Tag and delineates its mechanism for data sampling and retrieval. Section II also evaluates the power consumption involved with the mechanism. Section III shows experiments we conducted to investigate the viability of data retrieval by a moving-interrogator. Finally, Section IV concludes the paper.

II. DUAL INTERFACE PASSIVE TAG

This section introduces a Dual Interface Passive Tag known as “recorder tag” [8],[9] and describes its mechanism for data sampling and retrieval. We also conduct the evaluation of the power consumption of the recorder tag and discuss the power-saving achieved by the mechanism.

A. Recorder Tag Mechanism

A recorder tag comprises of a dual interface RF tag chip, antenna, a micro-processor unit (MPU hereafter) and sensors. The term “dual interface” specifically refers to the RF and baseband interfaces both of whom can access EEPROM in the RF tag chip. The tag is called the recorder tag as its functionality is focused on recording the data of the environment or objects to which the tag is attached. The prototype recorder tag is strictly a passive UHF RF tag that complies with the specification of an international standard [11] and is equipped with a temperature sensor, a luminance sensor, and 2 kilobits of user memory located in the RF tag chip (Figs. 2,3). The RF tag chip is Quanray QR2235 combo. The MPU in the prototype recorder tag is Renesus R8. We can implement other sensors in the recorder tag through standardized digital interface such as SPI or through an A/D converter.

With the baseband interface, sensor data can be delivered to, and stored in, the RF tag chip memory (EEPROM). With the RF interface, sensor data in the RF tag chip memory can be retrieved wirelessly by interrogator (Fig. 4). Moreover we can use the external connector to additional sensors. This should be extremely convenient for industrial applications.

Since the recorder tag is strictly a passive tag, unlike traditional sensor data retrieval, the interrogator needs not be concerned about synchronizing its timing for accessing the data with the period of wake (as opposed to sleep) for the target sensor. In other words, sensor data with this mechanism is permanently access-ready for the interrogator as long as the tag is in the interrogation area (Fig. 5).

B. Power Consumption Evaluation

The recorder tag has numerous chips and ports on its integrated circuit that each consumes electricity. The recorder

Fig. 2. Recorder Tag (Front)

Fig. 3. Recorder Tag (Back)

Fig. 4. Fundamental Structure of Recorder Tag
TABLE I
ELECTRICITY CHARGE ON MPU FOR WAKE MODE (CLOCK OPERATIONAL AT 2.5MHZ)

<table>
<thead>
<tr>
<th>Voltage[V]</th>
<th>Electricity Current[mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>1.2</td>
</tr>
<tr>
<td>Output</td>
<td>3.0</td>
</tr>
</tbody>
</table>

On the recorder tag circuit, 30% of input power is lost in the voltage conversion process. Thus, since we know both input and output voltage, the value for the output current $Y_e$ on 3V scale can be calculated as;

$$Y_e = \frac{(1.2 \times X) \times 0.7}{3.0}$$

where $X$ is the value of the input current. The input current indicates how much electrical current flows in the circuit with 1.2 voltage. The value excludes the current associated with the DC/DC converter (44uA). When MPU is operated on 2.5 MHz (construed as “in wake mode”), it charges 0.8uA, temperature sensor does 10.0uA and luminance sensor does 1.0uA.

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where $X$ is the value of the input current. The input current indicates how much electrical current flows in the circuit with 1.2 voltage. The value excludes the current associated with the DC/DC converter (44uA). When MPU is operated on 2.5 MHz (construed as “in wake mode”), it has an input current of 4.23mA. When the clock is stopped, it has the input current of 1.59mA, thus its output current is theoretically 440uA. (Table I and II).

Applying the above mentioned numbers enables us to calculate the average current $I_A$[mA] on given duty ratio, as in;

$$I_A = \frac{(n_s \times 1.59 + (N_s - n_s) \times 4.23)}{N_s}$$

where $n_s$ represents sensor sampling time and $N_s$ represents the sensing interval. Thus $N_s - n_s$ indicates the length of the sleep period.

Substituting the real values into $n_s$ and $N_s$, we obtain a relationship between sensing interval and battery life expectancy (when using an 800mAh battery). Battery Life Expectancy significantly improves as the sampling interval is set wider until it saturates around $x=30$ when the battery lasts for 21 days (Fig. 6). Further improvement requires the reduction of current flow on IC on its sleep mode. The existing recorder tag holds unused ports and chips that may well be removed. Circuit optimization specifically tuned for the scenario will theoretically decrease the current flow from its existing value of 440uA down to around 50uA, which yields approx. 187 days of battery life. To achieve the same data retrieval rate for the interrogator with the traditional sensor data retrieval model that does not utilize the proposed dual interface passive tag, we need to keep the sensor continuously ‘awake’ for the interrogator’s access, which gives us only 9.85 days of battery life (when using an 800mAh battery). Therefore, the proposed mechanism using the dual interface passive tag proves to be approximately 19 times as efficient in its power consumption.

III. DATA RETRIEVAL WITH MOVING-INTERROGATOR

This section aims to evaluate the viability of data retrieval with a moving-interrogator. Through experiments, we specifically inspected how the probability of successful data retrieval is affected when dynamically changing the following three factors:

1) **Accessed data size:** The amount of data that interrogator attempts to access may affect the rate for successful retrieval of data. The moving-interrogator only stays in the tag-readable area for a limited period of time. Thus, theoretically there should be a limit for the accessed data size against success...
rate. To access more data, the interrogator will need to stay in the tag-readable area longer thus having to pass at the slower speed.

2) **Distance between interrogator and tag:** In order for interrogator to be able to successfully access tag and retrieve its data, tag must receive a signal of the proper strength. The recorder tag has its reception sensitivity average of -8.46dBm. In the real radio propagation environment the signal strength diminishes typically in linear proportion to the distance the signal travels. If the interrogator is too close to the tag, the received signal strength indicator (RSSI) becomes too strong. Conversely, if the interrogator is too far away from the tag, the RSSI at tag becomes too weak. Therefore the moving-interrogator must travel along the path to keep the right distance from the target tag.

3) **Interrogator’s moving speed:** The interrogator’s moving speed is relevant to the data retrieval rate as the moving-interrogator only stays in the tag-readable area for a limited period of time. When moving at slower speed, for example, the interrogator stays in the tag-readable area for a longer period and it allows for more “query” opportunities, increasing the data retrieval rate.

A. **Data Size vs. Interrogation Time**

We first scrutinized, with an experiment, how the accessed data size affect the overall interrogation time (Fig.7). The experiment has the following procedure;

1) PC (commercial laptop) connects to and controls interrogator.
2) Interrogator interrogates recorder tag.
3) Battery Assisted Passive tag (BAP) [12] snoops the interrogator’s signals.
4) We measure the length of interrogation time.

We see from the result that it took approx. 10 milliseconds for 2 bytes access and 14 milliseconds for 24 bytes access. Multiplying the accessed data size by 22 times (220%) only resulted in 40% increase in access time. This indicates the inventory overhead is dominantly large in the overall access time (Fig. 8). Therefore for the later experiments we may conclude the success of inventory is synonymous with the success of data retrieval.

B. **Data Retrieval Rate vs. Interrogator’s moving speed**

We then conducted two other experiments (Experiment A and B) to inspect the influence of interrogator’s moving speed on the data retrieval rate.

1) **Experiments Overview:** We utilized a programmable attenuator that emulates moving-interrogator for tag. Moving-interrogator emulation adopts essentially the same method from moving-tag emulation discussed in [13]. The attenuation values are configured to reproduce the same RSSI profile measured in a real fading environment. The use of programmable attenuator facilitates the experiment dramatically with two major benefits. 1) by simply changing its clock frequency (attenuation switching interval), we can emulate different speed of interrogator and its resulting RSSI transitions for tag. 2) by simply incrementing/decrementing the envelope of the RSSI transition curve, which provides stronger/weaker RSSI for tag, we can emulate a different distance between the interrogator and the tag.

2) **RSSI at Tag vs. Interrogator Position:** First, in experiment A, we obtain a profile of RSSI at Tag vs Interrogator Position in a real fading environment. The experiment A (Fig.9) has the following procedure;

- Signal Generator (SG) is placed on top of a pallet truck that has a rotary encoder on its wheel.
- SG is connected to Antenna-1, a dipole antenna of 3dBm gain, and keeps transmitting at 953MHz, the center frequency of high power UHF RFID frequency allocation*. 
- Rotary encoder’s pulse is converted to voltage via a Frequency-Voltage(FV) converter and sent to a Data Recorder (DR).
- Spectrum Analyzer (SA) is connected to Antenna-2, another dipole antenna of 3dBm gain. SA receives and measures the signal from SG. The voltage measured in the centre frequency of 953MHz with the zero span measurement is then sent to DR.
- DR records both voltage data from the FV converter and the SA.

*Note that with the current (as of Feb.2010) Japan radio regulations, the use of high power RFID, over 20dBm EIRP, is not permitted in public roads. New regulations are expected to be enforced from April 2010 allowing up to 27dBm EIRP interrogator to be used in public roads.
Notes and Constraints; the voltage from the FV converter indicates the speed of the moving-interrogator whereas the voltage from the SA indicates the RSSI at tag. Antenna-1’s altitude is constant 30cm and Antenna-2 is at constant 0cm (altitude from the ground).

Figure 10 is a resulting RSSI profile we acquired. It shows that while RSSI at tag is generally stronger as the interrogator is in a closer position, the overall RSSI transition curve constantly fluctuates as the effect of fading. In Experiment B, the RSSI data profile obtained from Experiment A is used by the programmable attenuator to reproduce the RSSI pattern for tag, i.e., emulating the moving-interrogator for the tag. Experiment B (Fig.11) has the following devices;

- PC (commercial laptop); controls interrogator and checks if the inventory is successfully terminated.
- Interrogator; interrogates recorder tag on polling mode.
- Programmable Attenuator; sits between the interrogator and recorder tag and dynamically attenuates signals at the manually specified timing.
- BAP; snoops the interrogator signals and sends to the oscilloscope.
- Oscilloscope; observes and confirms if the manually executed attenuation actually occurred.

We change the read-clock of the attenuator to emulate different speed of interrogator. Attenuator’s read-clock is changed between 500[Hz], 1000[Hz], 2000[Hz], 5000[Hz] and 10000[Hz], which approximately correspond to 0.6[km/h], 1.2[km/h], 2.4[km/h], 6[km/h] and 12[km/h] respectively (Table III). Moreover, we decrease the attenuation level by 5[dBm] to 15[dBm], which in emulation brings the interrogator closer to the tag (Table IV).

Note and Constraints; we classify the data retrieval to be successful if the interrogator manages to complete an inventory for the target tag. The experiment does not check if the user data was also successfully retrieved, since it was established in a previous experiment that the inventory constitutes the dominant portion, we conclude the success of the inventory as the success of the whole data retrieval.

3) Result: The data retrieval rate gradually deteriorated as the read-clock increased, emulating a higher speed of interrogator. The data retrieval rate was the highest with +10[dBm] RSSI profile which translates to a distance of 10cm between tag and interrogator. The result indicates for example that the interrogator passing 10cm above the tag under the speed of 3km/h is likely to have nearly 100% of successful data retrieval (Fig. 12). The moving speed, 3km/h, can be increased by optimizing the anti-collision procedure and by enhancing the sensitivity of the recorder tag.

IV. CONCLUSION

This paper introduced real-world situations where one desires to retrieve sensor data from an arbitrary environment via a moving device, e.g., the maintenance of street lights and conduits. We then discussed the fundamental problem with...
such a system of retrieving sensor data through a moving-interrogator; 1) the compromise between power consumption by the sensor and data retrieval rate for the interrogator. 2) data retrieval agility for the moving interrogator. We then presented a solution of separating the timing of sensor-sampling and the timing of sensor-data retrieval. The proposed asynchronous data retrieval mechanism was facilitated by a dual-interfaced UHF passive RF tag called the recorder tag. Power consumption efficiency of the proposed data-retrieval method was discussed and compared with that of the existing method. Finally, we described three experiments conducted to evaluate the viability of data retrieval with the moving-interrogator.

a) Power Consumption: With the proposed method applied, the battery life in the recorder tag was significantly extended as the sampling interval (x) was set wider until it saturated around x=30 [minutes] when the battery lasted for 21 days. Further improvement requires the reduction of electrical current drain on the IC on its sleep mode. The existing recorder tag holds unused ports and chips that may well be removed. Circuitry optimization specifically tuned for the case of sensing temperature and luminance will theoretically decrease current flow from its existing value of 440uA down to around 50uA, which should yield approximately 187 days of battery life, achieving an approximately 19-times longer battery life than that of the traditional mechanism.

b) Data Retrieval Rate: The data Retrieval Rate gradually deteriorated for a higher travelling speed of interrogator. 100% data retrieval rate was attained when the distance between the tag and the interrogator was 10cm for a 27dBm EIRP moving interrogator. The result indicates that the interrogator passing 10cm above the tag under the speed of 3km/h is likely to result in nearly 100% of successful data retrieval. The moving speed, 3km/h, can be increased by optimizing the anti-collision procedure and by enhancing the sensitivity of the recorder tag.

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