Abstract—Measuring multiple physical quantities are increasingly being demanded in commercial, biomedical and generally in ubiquitous applications. Although the recent emergence of passive sensor enabled RFID tags (sensor tags) provide new opportunities for these types of applications mainly due to the extended operational life and the small form factor, the energy harvesting nature of sensor tags hinders the use of multiple sensors in a single platform because of the requirement of additional energy to operate multiple sensors and subsequent reduction in the throughput. In this paper, we propose three, fast and energy efficient multi-sensor data retrieval approaches to obtain sensor data from sensor tags. We implemented a sensor tag with two sensors, an accelerometer and a barometer. Our extensive experiments on power consumption, operational range and throughput using the developed sensor tag revealed that, the proposed approaches can successfully be used for multi-sensor data retrieval and indicates that they can effectively be used in a range of real-world ubiquitous sensing applications such as fall prevention and food safety monitoring.

I. INTRODUCTION

Measuring and understanding physical quantities are paramount for commercial [1]–[3] (eg: in cold chain managements where temperature is constantly monitored), medical applications [4] and more broadly enabling ubiquitous monitoring [5]. Recent emergence of passive sensor enabled Radio Frequency Identification (RFID) tags (hereafter referred to as sensor tags) such as the Wireless Identification and Sensing Platform (WISP) [6] developed by Intel Research provide new prospects to measure physical quantities using low cost devices [7] without batteries. Furthermore, such sensor tags have a small form factor and can even be embedded permanently within other equipment as discussed in [6].

Real-world applications demand retrieval of multiple physical quantities. For instance, sensing multiple types of gases is paramount for monitoring air pollution in different environments [8], [9], monitoring temperature and humidity simultaneously to ensure food safety [10] and retrieval of barometric pressure and movement information for older people monitoring [11] require multi-modal sensing devices.

However, there are two main issues associated with embedding multiple sensors in a single passive sensing platform. Firstly, sampling multiple sensors require an excessive amount of power. For instance, operating multiple analog-to-digital converters (ADC) simultaneously place a larger burden on harvested power, especially due to the large peak current requirements of ADCs. Even though the sensors are sampled sequentially the excessive energy consumption may still not be satisfied using harvested energy. This large electrical energy requirements are detrimental to the effective operation range of sensor tags [12] as harvested power is inversely proportional to the squared distance between the sensor tag and the RFID reader antenna according to the Friis transmission equation [13]. Secondly, embedding multiple sensors lead to delays due to the additional sampling time and increased data processing time that reduce the throughput of sensor tags and, consequently, the overall performance of the sensor tag.

Operational range and throughput for sensor tags are important parameters that typically depend on the application. For instance, applications such as fall detection requires a larger operational range where as gesture recognition applications favor higher throughput to be able to capture highly dynamic movements. Therefore, in this paper, we investigate three sensor data retrieval schemes, with differing performance characteristics, suitable for sensor tags with multiple embedded sensors. We summarize our contributions below:

- We propose three sensor tag data retrieval schemes for multiple sensors embedded in a single sensor tag: i) sequential, ii) parallel and iii) alternative. These schedules determine when to sample the sensor and transmit data back to RFID readers.
- We evaluated the proposed schedules using a multi-sensor sensor tag developed based on the WISP by embedding a barometer as an additional sensor along with the accelerometer. Our analysis and extensive experiments revealed that the parallel schedule has the least delay, but has the highest power consumption; in contrast, alternative schedule has the highest delay and demonstrated the largest operational range while also being the most energy efficient multi-sensor data retrieval schedule.

Remaining sections of the paper are organized as follows: Section II discusses related work; Section III presents our proposed multi-sensor data retrieval approaches; Section IV details the implementation; Section V presents the experiments conducted and results. We conclude the paper in Section VI.

II. RELATED WORKS

There are two common approaches to retrieve sensor data from a sensor tag: i) Read-by-Command approach (RBC) and ii) Data-in-ID approach (DID). In the RBC approach, sensor data are acquired using the READ command [14] and this
process is illustrated in the sequence diagram in Fig. 1(a). First, a sensor is sampled and then the data are stored in a non-volatile memory, typically in an Electrically Erasable Programmable Read-Only Memory (EEPROM) unit of a tag. Subsequently, sensor data stored in a tag’s non-volatile memory are read using the READ command by specifying a pointer to the memory location with the desired data as defined in the Electronic Product Code (EPC) Air Interface protocol [14]. This approach requires several reader-to-tag-to-reader communication cycles as illustrated in Fig. 1(a). Storing data into an EEPROM not only consumes considerable power (148 µW for writing [15]) but also takes a considerable amount of time. In case of sensor tags, this approach is limited by the high power consumption and significant reduction in throughput.

A recent study by Igarashi et al. [16] proposed a network architecture to acquire data stored in an EEPROM of a sensor tag by first defining a structured memory and subsequently accessing a specific memory address with the desired sensor data. In this study the authors proposed a memory address resolution scheme to reduce the time to locate the interested sensor data and thereby reduce the overall data retrieval latency. However, their approach is not geared towards energy efficiency.

Alternatively, the Data-in-ID approach was utilized by Alanson et al. [6] for sensor data retrieval from a WISP. In this approach, as shown in Fig. 2, portion of the 96-bit EPC is replaced by sensor data, thereby transmitting data in an inventory session. Sensor tags such as WISPs which utilize this approach initially sample the onboard sensors when adequate power is harvested. Upon receiving a QUERY command from an RFID reader, the sensor tag responds with a 96-bit EPC where the sensor data is embedded within the EPC. Consequently, part of the EPC is used to piggyback the sensor data. It is important to note that, if the total time taken to transmit acquired sensor data and sample on-board sensors exceeds the interval over which the RFID reader waits for a response, then the sensor tag has to wait for a subsequent QUERY command to transmit the sensor data; this reduces the throughput of the sensor tag. This approach enables the use of off-the-shelf RFID readers to acquire sensor data, but require special software to de-embed the data in the ID [17]. Although the WISP developers have included a number of on-board sensors, such as a capacitance sensor, a voltage sensor, a thermometer and a 3D accelerometer, sampling multiple sensors simultaneously have not been considered in the past. All of these sensors on a WISP are analog components and are sampled using the Microcontroller’s (MCU’s) internal ADC. The current WISP firmware is designed to sample a single sensor that is specified at the firmware compile time, hence in the present state, the WISP cannot sample multiple sensors simultaneously. Therefore, we are motivated to investigate a fast and energy efficient multi-sensor data retrieval schemes from sensor tags needed for a wide array of real-world applications.

### III. Multi-Sensor Data Retrieval

A multi-sensor sampling approach for passive sensors should have two desired properties: i) high throughput; and ii) high power efficiency. As discussed in Section II, Read-by-Command (RBC) approach, which is defined in the EPC standards, requires a considerable amount of power and incurs significant delays. Therefore, in order to reduce power consumption and communication delays, we base our multi-sensor data retrieval approaches on the DID approach.

Efficiency increases the operational range while throughput determines the quantity of the sampled data. In order to analyze and compare multi-sensor data retrieval approaches, we quantify the afore mentioned properties as follows. We denote the number of sensors embedded in an RFID platform to be \( n \) and the sampling time of \( i^{th} \) sensor, \( i \in \{1 \cdots n\} \), to be \( t_{si} \). We denote the data transmission time for a sensor tag

\[1\]http://wisp.wikispaces.com/Wisp+4.1+DL
TABLE I
CHARACTERISTICS OF SENSOR SAMPLING SCHEDULES

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Time delay</th>
<th>Energy consumption rate</th>
<th>Dedicated ADC</th>
<th>Additional control logic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequential</td>
<td>$\sum_{i=1}^{n} t_{si} + t_{t}$</td>
<td>$\frac{E_{n}}{(\sum_{i=1}^{n} t_{si} + t_{t})}$</td>
<td>necessary</td>
<td>none</td>
</tr>
<tr>
<td>Parallel</td>
<td>$\max_{i}(t_{si} + t_{t})$</td>
<td>$\frac{E_{n}}{(\max_{i}(t_{si} + t_{t})}$</td>
<td>necessary</td>
<td>none</td>
</tr>
<tr>
<td>Alternative</td>
<td>$\sum_{i=1}^{n} (t_{si} + t_{t})$</td>
<td>$\frac{E_{n}}{\sum_{i=1}^{n} (t_{si} + t_{t})}$</td>
<td>optional</td>
<td>large</td>
</tr>
</tbody>
</table>

TABLE II
SPECIFICATIONS OF THE SENSORS USED IN MULTI-SENSOR WISP

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Typical sample time</th>
<th>Peak current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer (ADXL330)</td>
<td>4 ms [18]</td>
<td>1.05 mA [18]</td>
</tr>
<tr>
<td>Barometer (MS5611-01BA03)</td>
<td>8.2 ms [19]</td>
<td>1.4 mA</td>
</tr>
</tbody>
</table>

condition: 2.2V supply; 25°C, maximum resolution.

When these sensor sampling schedules are considered, it is expected for the alternative schedule to have the greatest operational range as it has the lowest energy consumption rate. The parallel schedule is expected to have the highest throughput as the time to sample sensors is minimum but only when the sensor tag is adequately powered, particularly when the sensor tag is near an antenna. The sequential schedule provide a compromise between the parallel schedule and the alternative schedule.

IV. IMPLEMENTATIONS

In this section, we first discuss the hardware developments and later we discusses the upgrades to the WISP firmware to implement the three proposed multi-sensor data retrieval schedules.

A. Hardware modification

In order to test the multi-sensor performance, we built a new platform based on the WISP 4.1DL\(^2\). As shown in Fig. 4, a new digital barometer is added alongside the existing 3-axis accelerometer. Both sensors acquire power from the MCU General Purpose Input/Output (GPIO) ports while the 3-axis accelerometer is sampled by the MCU’s internal ADC, but the barometer uses its own ADC. The digitized barometer data are transferred to the MCU through a Serial Peripheral Interface (SPI) bus. Specifications of these sensors are given in Table II. All the other parts of the circuit are identical to the original WISP 4.1DL.

The Fig.5 compares the new Multi-Sensor WISP to the original WISP 4.1DL. Due to the fabrication issues the outer border of the circuit board was kept and hence our Multi-Sensor WISP is visually larger than the WISP.

B. Sequential schedule

We first sample the barometer and then the accelerometer to realize the sequential schedule. The barometer consumes

\(^2\)http://wisp.wikispaces.com/Wisp+4.1+DL
higher power (see Table II) and successful sampling of the barometer increases the probability of the sensor tag to sample the less energy consuming accelerometer. The total time to sample both the sensors is approximately 12 ms, which is the sum of the individual sensor sampling times.

Figure 7 illustrates the format of the tag ID used to transmit data using the sequential sampling schedule. The data from the accelerometer is stored using 30 bits and the data from the barometer is stored using 24 bits.

C. Parallel schedule

As mentioned in Section IV-A, the accelerometer is sampled by the ADC integrated in the MCU and the barometer is sampled by its on-chip ADC. Having two ADCs to sample each sensor enabled the implementation of parallel sensor sampling schedule. We designed the parallel process as shown in Fig. 8. First, we setup the barometer and then the accelerometer.

The latter is coordinated by soft instructions and complete early. The barometer takes a longer time (see Table II) and raise a hardware interruption to notify the MCU to receive results. Generally, the sensor response time is trivial because by specifying interruption priorities any sensor can be sampled as described in the parallel schedule. In this schedule, data is sent using the same format as in the sequential schedule which is shown in Fig 7.

D. Alternative schedule

The alternative schedule is similar to the single sensor case, but each sensor is sampled and its data are transmitted separately in each session as shown in Fig.9. In our implementation, upon powering of the sensor tag, we first sample the accelerometer and then the barometer. The sensors are alternately sampled while the tag is alive and this process repeats each time the sensor tag is powered.

Figure 10 illustrates the format of the tag ID for the alternative schedule. This organization is similar to the tag ID
V. EXPERIMENT AND RESULTS

In our experiments, we mainly evaluate the throughput and efficiency of each sensor data retrieval approach: i) DID and ii) RBC and the proposed multi-sensor data retrieval schedules. We conducted four types of experiments: i) time delay; ii) power consumption; iii) communication range; and iv) read rate.

All the experiments were conducted using an Impinj Speedway Revolution R420-GX11M reader attached to a 6 dBi circularly polarized antenna. We employed two identical original WISP 4.1DL sensor tags from the same batch to evaluate the performance of DID and RBC data retrieval methods. Due to the manufacturing issues, the efficiency of RF front end varies for each individual Multi-Sensor WISP tags and hence one multi-sensor tag (see Fig. 5) was used. We reprogram the same multi-sensor tag to implement the three sensor sampling schedules for our experiments. We considered acquiring data from all the sensors as a successful reading. In the case of alternative schedule, retrieval of data from both sensors (barometer and accelerometer) sequentially in two sample-transmit cycles were considered as a successful reading.

1) Time delay: We utilized two standard WISPs and programmed them to operate on DID and RBC. For DID approach, we measured the time taken to inventory a sensor tag. In the case of RBC approach, we measured the EEPROM write time, time taken to inventory the tag, EEPROM read time and time to read the memory of the sensor tag by specifying the exact memory location (offset: 0) and the required amount of information (2 words which corresponds to 32 bits). During the experiment, the WISP is powered by an MSP430 debugger with a constant 2.5 V \( V_{cc} \) to eliminate timing errors caused by low power sleep and failed EEPROM operations as the EEPROM is sensitive to the voltage level during writing. During the experiment the distance between sensor tags and the RFID antenna is fixed at 40 cm. It is not possible to directly measure the EEPROM writing time using the data from an RFID reader. Therefore, we modified the WISP firmware to raise a GPIO pin on sensor data retrieval and lower it upon a backscatter event. The fluctuation on the GPIO pin can be easily captured by a logic analyzer or a digital oscilloscope to obtain the required measurements.

2) Power Consumption: As specified in WISP circuit schematic, the harvested energy is stored in a 10 \( \mu \)F monolithic capacitor. The electrical energy in a capacitor with capacitance \( C \) is proportional to the square of capacitor’s terminal voltage, \( V_{cap} \), as given by \( E_{cap} = \frac{1}{2} CV_{cap}^2 \). According to the description in Sample et al. [6], the hardware voltage supervisor monitors \( V_{cap} \) and generates an interrupt when \( V_{cap} > 2 \) V to switch the MCU from Power Save Mode to Active Mode. The system then starts sampling sensors and RFID protocol related calculations. When the required power is less than the harvesting power, the energy storing capacitor is drained to provide the deficit and \( V_{cap} \) varies as the WISP process into sensor sampling event. Therefore, measuring the voltage difference from MCU become alive (when \( V_{cap} > \) threshold) and the end of sample-transmit session (end of backscatter) will give a quantitative indication of power consumption. This voltage variation can be easily measured as shown in Fig. 11 by using a Digital Oscilloscope internal math function \( 2V - V_{min} \) and we take the mean value over 256 session.

3) Operational Range: This test is designed to measure the maximum operational distance of the sensor tag under DID and RBC configuration as well as the proposed sensor sampling schedules. The experiment is conducted inside an anechoic box as shown in Fig.12. Initially, we placed a sensor at position 0 cm from the reader antenna and then the tag is gradually moved away from the antenna. When the interval between two sensor readings exceed 5 s, we consider this distance to be the maximum operating range. In order to avoid
any possible interference, e.g. multi-path reflection and power backscatter from another WISP, measurements related to each WISP were taken separately from other WISPs.

4) Read rate: Read rate directly measures the throughput of the system. A higher read rate is indicative of sensor tag’s ability to capture detailed information in terms of timeliness and resolution. This experimental setup is similar to the delay test where the tag is fixed at 1 m from the RFID reader antenna inside the anechoic box. Here, sensor tags were powered by the harvested energy unlike in delay evaluation. We use an in-house developed data logging application to obtain readings and subsequently to calculate the read rates.

A. Data-in-ID approach versus Read-by-Command approach

Here, we measured the throughput for sensor data retrieval, energy consumption and read range. The main goal of these experiments is to empirically compare and contrast the DID and RBC approaches.

Table III show the results for the time delay experiment for acquiring acceleration data using DID and RBC approaches. It is clear from this table that the latency for RBC is on average 21.41 ms, approximately 3 times that of DID approach. Therefore, using DID approach is unfavorable for high throughput applications.

Table IV lists the results for power consumption test and read range test for DID and RBC approaches. From these results we can see that there is a considerable change in $\Delta V_{cap}$ and hence in $\Delta E$ in case of RBC. This suggests that there is a higher probability for the WISP to brownout while RBC is used compared to when DID is used. The high electrical energy requirement for RBC will adversely impact the communication range, mainly because at a higher distance the harvested power is insufficient to support the RBC approach. As shown in Table IV, the operational range of DID is approximately three fold higher than RBC.

From these experiments, i.e. delay, power consumption and operational range, it is evident that the DID performed better than RBC approach. Therefore, DID approach can be used as an energy efficient multi-sensor data retrieval approach.

B. Proposed multi-sensor data retrieval schedules

We conducted three experiments: i) power consumption; ii) communication range; and iii) read rate to analyze the three proposed multi-sensor sampling schedules based on the DID approach.

1) Power consumption: We conducted the power consumption experiment as described earlier in Section V-2. Figure 13 illustrates the variation of terminal voltage of the energy storing capacitor, $V_{cap}$, and the backscatter events for each multi-sensor data retrieval schedule. From the combination of the two measurements, we can infer the internal state of the WISP. In Fig. 13, successful sampling of the accelerometer can be identified from the stylized three-peak saw tooth. This saw tooth reflects the successive sampling of the three axes of the accelerometer. A successful sample-transmit session of the barometer is indicated by a large slope which corresponds to a drawing of more power. Backscatter event suggests a successful transmission of sensor data.

When the Multi-Sensor WISP operates in the sequential schedule, (see Fig. 13(a)) there are some failed readings due to insufficient power or a SPI transmission error. For example, at time $\approx 0.4$ s the MCU failed to receive the interruption from the barometer, then the system was reset as a consequence of the Watchdog Timer (WDT) timeout. Figure 13(a) shows a reset at time $\approx 0.3$ s caused by a low voltage as a result of the barometer drawing a large current. Similar situations can also be observed at time $\approx 0$ s and time $\approx 0.45$ s where the accelerometer was drawing excessive power while reading the second axis resulted in system resets.

In case of the parallel schedule shown in Fig. 13(b), we can see that there are larger voltage drops due to the simultaneous sampling of the accelerometer and the barometer. There are four successful retrieval-report sessions. At time $\approx 0.15$ s the system was reset due to an SPI error. The label $\delta$ shows an invalid session. After the accelerometer data is retrieved, the barometer failed to respond the SPI read command and
then the system times out; therefore no backscatter event was generated in this session.

Figure 13(c) shows the terminal voltage ($V_{cap}$) of the energy storing capacitor and the backscatter activities of the Multi-Sensor WISP when it is operating under the alternative schedule. We can observe that, there are some unsuccessful readings at time $\approx 0.1$ s and time $\approx 0.25$ s. They are failed barometer reading sessions and indicate that the barometer is more likely to fail as it can consume up to 1.4 mA (peak current) the analog to digital conversion (see Table II).

Table V shows the power consumption calculated using $V_{cap}$. Using the total time, $t_{256}$, taken to complete 256 reading cycles, the energy consumption rate $\rho_c$ can be calculated as $\rho_c = \frac{\Delta E_{256}}{t_{256}}$. We can see that the sequential approach has a slightly lower voltage variation, consequently a lower energy change per cycle. However, the alternative schedule displays the minimum energy consumption due to the lower duty cycle.

2) Operational range: This experiment is conducted in an anechoic box as described in Section V-3. Table VI shows the mean values of the maximum operational distances of the three multi-sensor data retrieval schedules.

From Table VI, we can see that both sequential and parallel schedules have a shorter operational distance compared to the alternative schedule. It is important to note that there is an inverse relation between the operational distance and the energy consumption rate. The alternative schedule depicts the highest operational range and the minimum energy consumption rate. Similarly, the parallel schedule showed the minimum operational range and maximum energy consumption rate. As expected (see Section III), lower energy consumption rates result in higher operational distances (see Table VI).

3) Read rate: Figure 14 illustrates the read rate of the WISP as the reader transmission power is decreased. We can see that, when adequate power is present the parallel schedule has the highest read rate, but it is closely followed by the sequential schedule. This is due to the fact that, both schedules have similar energy consumption rates as shown in Table V. The lower read rate for the alternative schedule is because it requires multiple inventory sessions (two in this experiment as two sensors are used) to transmit the data from all the sensors embedded in the sensor platform.

It is also important to note that, as expected, the alternative schedule can perform even when there is less power to be harvested. When transmission power is at 20dBm, both the parallel schedule and the sequential schedule were unresponsive. At this instance the alternative schedule was responding, but at a very low read rate. These results closely correlate with the range test results (see Table VI) where the harvested power is reduced as the tag moves further away from the RFID antenna.

VI. CONCLUSION AND FUTURE WORK

In this paper, we presented the design, implementation and evaluation of three data retrieval approaches for Multi-Sensor
Passive RFID Tags. These approaches were designed based on the Data-in-ID approach.

From analysis and extensive experiments, we show that the alternative schedule has a longer operational range. Both parallel and sequential schedules performed similarly in terms of operational range and power consumption. Although the sequential schedule showed a slightly lower read rate compared to the parallel schedule, sequential schedule was able to sample data at a lower energy than required by the parallel schedule. This indicates that the sequential schedule perform marginally better than the parallel schedule when two sensors are embedded in a sensor tag. These properties may change when more sensors are used as indicated in Section III. These three sensor sampling schedules are energy efficient and faster than the traditional sensor data retrieval approach which is Read-by-Command. Proposed multi-sensor data retrieval approaches have different characteristics and hence the most suitable one can be selected according to application needs.

Although we have implemented these sensor sampling schedules using only two sensors, they can be used to sample more than two sensors as these sensor sampling schedules bare no assumptions on the number of sensors used. To account for multiple sensors and more data requirements, 256 bit EPC or a larger EPC can be used instead of the 96 bit EPC used currently. Incorporating more sensors, we are expecting to observe the same, but more distinctive properties. For instance, read rate of the sequential schedule and the parallel schedule is similar with two sensors (see Fig. 14), but we expect the read rate of the sequential schedule to be significantly lower than the parallel schedule.

There are two main limitations of this study. First, the size of the data that can be transmitted is limited by the EPC. Although a larger EPC could be used, transmitting data in orders of several kilobytes may require multiple inventory cycles and subsequently result in larger delays. However, using Read-by-Command approach can acquire such data by using one inventory command and one read command, which is more efficient. Secondly, we have evaluated these multi-sensor data retrieval schedules using only two sensors. To further analyze the properties of the proposed approaches empirically, a sensor tag with multiple sensors need to be implemented.

In conclusion, this study provides new prospects for using sensor tags in multi-modal sensing to realize a wide range of applications.

VII. ACKNOWLEDGEMENT

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