Abstract—In recent years we have seen a tremendous growth in applications of passive sensor-enabled RFID technology by researchers; however, their usability in applications such as activity recognition is limited by a key issue associated with their incapability to handle unintentional brownout events leading to missing significant sensed events such as a fall from a chair. Furthermore, due to the need to power and sample a sensor the practical operating range of passive-sensor enabled RFID tags are also limited with respect to passive RFID tags. Although using active or semi-passive tags can provide alternative solutions, they are not without the often undesirable maintenance and limited lifespan issues due to the need for batteries. In this article we propose a new hybrid powered sensor-enabled RFID tag concept which can sustain the supply voltage to the tag circuitry during brownouts and increase the operating range of the tag by combining the concepts from passive RFID tags and semi-passive RFID tags, while potentially eliminating shortcomings of electric batteries. We have designed and built our concept, evaluated its desirable properties through extensive experiments and demonstrate its significance in the context of a human activity recognition application.

Index Terms—sensor-enabled RFID tag; WISP; brownout; power harvesting; hybrid-powered; activity recognition

I. INTRODUCTION

Sensor-enabled RFID tags are being developed due to their extensive potential to add value over traditional identification-only tags in a wide range of applications such as cold chain management [1], indoor localization and the monitoring of elderly people to ensure their safety using body-worn sensor-enabled tags [2], [3] and, in general, ubiquitous sensing applications. A particularly attractive capability of passive sensor-enabled RFID tags is their ability to sense and report physical phenomenon such as human movements or barometric pressures without relying on the limitations imposed by electric batteries. Wireless Identification and Sensing Platform (WISP) [4] developed by Intel Research is a case in point of an emergence in passive, low cost and sensor-enabled RFID technology by researchers; however, their usability in applications such as activity recognition is limited by a key issue associated with their incapability to handle unintentional brownout events leading to missing significant sensed events such as a fall from a chair. Furthermore, due to the need to power and sample a sensor the practical operating range of passive-sensor enabled RFID tags are also limited with respect to passive RFID tags. Although using active or semi-passive tags can provide alternative solutions, they are not without the often undesirable maintenance and limited lifespan issues due to the need for batteries. In this article we propose a new hybrid powered sensor-enabled RFID tag concept which can sustain the supply voltage to the tag circuitry during brownouts and increase the operating range of the tag by combining the concepts from passive RFID tags and semi-passive RFID tags, while potentially eliminating shortcomings of electric batteries. We have designed and built our concept, evaluated its desirable properties through extensive experiments and demonstrate its significance in the context of a human activity recognition application.

In this paper, we present our concept, preliminary design, implementation and evaluation of the hybrid powered RFID sensor tag based on the WISP in [4] to develop a Hybrid powered WISP (H-WISP). The H-WISP combines the advantages of the passive and semi-passive tags, which supports a power storage device together with a Hybrid Power Management Unit (HPMU) to realize the automatic switching between tag operating modes shown in Fig. 1: i) passive & charging; ii) semi-passive; and iii) off mode. We implemented the proposed hybrid RFID sensor tag approach based on the WISP to realize the H-WISP. Through experiments we show that supercapacitors are suitable for the present implementation. Using a supercapacitor as an internal power storage device, we show that the H-WISP can achieve significant operational range, higher read rate particularly when energy to be harvested is limited and is able to successfully operate under sudden brownout events.

Remaining sections of the paper are organized as follows: Section II presents our proposed architecture of the H-WISP; Section III discusses our implementation in detail; Section IV presents the conducted experiments and results; a real-world application is presented in Section V; and Section VI discusses
related work. We conclude the paper in Section VII.

II. ARCHITECTURE

Our conceptual architecture for realising a hybrid powered RFID sensor tag based on the WISP [4] is illustrated in Fig. 2. On a WISP, before the Analog Front End (AFE), an antenna and an impedance-matching circuit are installed. The incoming RF energy is rectified by a power harvester into DC voltage to power the system while extracting the amplitude shift (ASK) data stream by following the envelope of the RF carrier wave using the demodulator. Then, the onboard MSP430 microcontroller (MCU) reads this extracted baseband waveform to receive downlink data via the modulator circuit. The harvested power is also used to energize the onboard sensors in the system.

Our main objective is to demonstrate the hybrid powered RFID tag concept capable of addressing the brownout issue while maintaining the original functionalities of the WISP. Therefore, we included the key functional element of the hybrid powered tag approach, the Hybrid Power Management Unit (HPMU), between the power harvester and Voltage Regulator 1 as shown in Fig. 2. The HPMU consists of: i) a power manager—a sophisticated power management circuit; ii) an internal power storage device; iii) a voltage regulator (Voltage Regulator 2); and iv) software module on the MCU to analyze variations in the output voltage from the power harvester, where this voltage is inversely proportional to the squared distance from the tag to the RFID reader antenna, and manage the power to the H-WISP by controlling the HPMU.

More specifically, when the converted voltage from the power harvester is sufficiently high, voltage is regulated through Voltage Regulator 1 and the MCU is powered similar to the original WISP. At this instance the power manager also charges the internal power storage device (Passive & charging mode). When the supplied voltage from the power harvester drops below the operating voltage of the MCU, the storage device powers the MCU and the tag operates in Semi-passive mode. When the output voltage is lower than a critical value, the WISP system is put into the Off mode to conserve harvested power stored in the energy storage device while the tag waits for a wake up signal to enter into either Passive & charging mode or Semi-passive mode.

III. IMPLEMENTATION

This section describes the hardware and software implementations of the hybrid power management unit and the H-WISP. In particular, three main factors need to be considered before realizing the proposed concept in the form of a H-WISP. Firstly, the HPMU should consume negligible power compared to the power consumption of the existing WISP design. Secondly, the limited output voltage and current from the power harvester must now be actively and carefully managed using a comprehensive power management circuit. Thirdly, the selection of an Power Storage Device should consider the overall operational characteristics of the tags, such as intermittent and potentially large number of charging and discharging cycles, to ensure the long term performance of applications built using hybrid powered RFID sensor tags such as the H-WISP developed in this article.

A. Hardware

In order to develop a very low power HPMU we utilized the fully integrated EnerChip (CBC3105) with a small form factor to implement the power manager within the HPMU. EnerChip is an intelligent solid state energy storage device, which charges itself with a controlled voltage using an internal charge pump that operates from 2.5 V to 5.5 V during normal operation [5]. The resulting Hybrid Power Management Unit (HPMU) circuitry is depicted in Fig. 3. When the input voltage to EnerChip falls below a threshold voltage selected by the user, an event will be signalled by the EnerChip to route power from the integrated battery (or as in our implementation the external Power Storage Device in Fig. 3) to provide the output voltage. When the input voltage is greater than the pre-selected threshold, the input power is used to both charge the internal battery and supply the output power. The charge pump in the EnerChip can be controlled using the ENABLE pin (see Fig. 3a) to optimize the current consumption and to take advantage of fast recharging.

In the HPMU, as shown in Fig 3, the EnerChip input voltage is through a voltage doubler to reduce the effective threshold voltage at which the EnerChip switches from charging the Power Storage Device to discharging the Power Storage Device. We used equal values of resistors (R1 and R2) to set the threshold voltage to 2.5 V, the minimum permissible, while the voltage doubler reduces this to an effective threshold voltage of 2 V.

When the EnerChip input voltage exceeds the specified threshold, the output voltage is equivalent to the input voltage but when the input voltage is below the specified threshold, the output voltage is typically maintained at 3.3 V [5]. When the sensor tag is near an antenna, the harvested voltage through the EnerChip, which is around 5 V, is sufficient to damage the MCU as the MCU works between 1.8 V to 3.6 V [6]. Therefore the output from EnerChip to the MCU is regulated to prevent possible damage from a high output voltage as well as provide a controlled supply voltage to the MCU.

We selected the triple analog switch NLA54783, voltage doubler MAX1724, voltage detectors S1009 with 1 V and
2.5 V thresholds, voltage regulator NCP583, and level translator NSV1T244 due to their ultra low power consumption. The 2.5 V voltage detector is connected directly to $V_{OUT}$, the output voltage from the power harvester. The MCU controls the usage of the 1 V voltage detector using the analog switch connected to pin P3.5 on the MCU. The initial state of this switch is in off state, i.e. not connected to the 1 V voltage detector. The remaining two switches are connected directly to $V_{OUT}$ and both are connected to the MCU’s pin P3.4. One switch is used to enable the selective use of the voltage doubler which is disconnected at the start or after a hardware reset. The second switch connects $V_{OUT}$ directly to the EnerChip input pin, by-passing the voltage doubler, and is set to on state at the beginning or after a hardware reset. The regulated voltage $V_{reg}$, after the voltage regulator in Fig. 3a, powers the analog switch and voltage detectors.

The outputs of voltage detectors are connected to the MCU using two level translators that transform the analog signals from voltage detectors to digital signals. The externally sensed voltage signals support the dynamic management of the HPMU and the realisation of the power cycle of the H-WISP (see Fig. 4). In particular, the 1 V voltage detector together with the level translator are added so that the MCU can differentiate the incoming voltage in order to determine whether to shutdown or activate the sensor tag. Then, whether the voltage doubler, which is required for effectively lowering the threshold voltage of the EnerChip to 2 V, to be used or not is determined by the 2.5 V voltage detector along with a level translator.

EnerChip has a $5 \mu$Ah integrated battery that is inadequate for maintaining the power supply beyond several seconds. Therefore, we disconnected the integrated battery and connected the $V_{CHG}$ shown in the Fig. 3a to an external Power Storage Device.

HPMU operation can be summarized as follows. When the output voltage $V_{OUT} > 2.5$ V, this voltage simultaneously powers the H-WISP and charges the power source through the EnerChip. When $2 < V_{OUT} < 2.5$ V, then voltage is switched through the voltage doubler to boost the voltage over 2.5 V to continue to ensure simultaneous charging and powering of the MCU and sensors. When $V_{OUT} < 2$ V all the three switches are used to select the 1 V voltage detector as well as the voltage double to allow either a switch to off mode or semi-passive mode in case of adequate harvested power. In the meantime, the Power Storage Device will be discharged through EnerChip to power the H-WISP. When $V_{OUT} < 1$ V, the H-WISP will be automatically turned off or enter into Off mode (see Fig. 1).

This selective usage of peripheral circuits under the control of the MCU is designed to reduce the overall power consumption of the HPMU. Although an additional analog switch and a voltage detector are added in this design, their use can reduce overall power consumption by turning unnecessary devices off. For instance, during the charging stage 1 V voltage detector is turned off. Furthermore, voltage doubler is only turned on when it is required, i.e. when $2 < V_{OUT} < 2.5$ V. This mechanism helps the H-WISP to consume 100 $\mu$W less power, on average, than solely using the EnerChip to realise the H-WISP.

In addition to the circuitry shown in Fig. 3a, a surface mount LED was also included in the prototype design to observe the internal status of the HPMU, (i.e. charging or discharging).

**B. Software**

In addition to regular functions performed by the WISP MCU such as sampling sensors and implementing EPC Class 1 Generation 2 communication protocol, the MCU in the H-WISP is also required to control the HPMU.
The operational power cycle of the MCU is shown in Fig. 4. External interrupts from either the voltage supervisor signal or the bit line communication interrupt drive an event in the system. The diagram shows that the MCU is put into low power mode between events to conserve power.

The H-WISP has two active modes and a semi-passive mode as shown in Fig. 4. Initially, when there is sufficient energy, the tag samples the onboard sensors and creates the EPC-compliant tag ID with the associated cyclic redundancy check (CRC). Then, the firmware waits for an RFID query command, which initiates the second active mode ‘Receive and Transmit’ where the MCU responds with the generated ID if the query is acknowledged. During the above process the tag operates similar to a conventional passive sensor-enabled tag. Unlike the original WISP, if an insufficient voltage is identified, the H-WISP firmware determines whether to transition into the semi-passive mode or power save mode according to the minimum threshold, thus preventing a possible brownout. The H-WISP can also transition into semi-passive mode directly from power save mode when the voltage exceeds the minimum threshold, reducing cold startup times typical of a WISP [7]. Furthermore, the MCU sends low or high level signals to turn on or off the charge pump of the power manager in HPMU via the ENABLE pin. The flow of the proposed software design of the HPMU is shown in Fig. 5.

**Table I: Common rechargeable power storage technologies**

<table>
<thead>
<tr>
<th>Type</th>
<th>Nominal Voltage (V)</th>
<th>Energy Density (Wh/kg)</th>
<th>Power Density (W/kg)</th>
<th>Self-Discharge Rate in month</th>
<th>Charge/discharge Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel-Cadmium</td>
<td>1.2</td>
<td>40–60</td>
<td>150</td>
<td>20%</td>
<td>1500</td>
</tr>
<tr>
<td>Nickel-metal Hydrid/LED</td>
<td>1.2</td>
<td>30–80</td>
<td>250–1000</td>
<td>30%</td>
<td>500–1500 [10]</td>
</tr>
<tr>
<td>Lithium-ion Polymer</td>
<td>3.7</td>
<td>130–200</td>
<td>3000</td>
<td>5%</td>
<td>500–1000</td>
</tr>
<tr>
<td>Thin Film Lithium</td>
<td>3.7</td>
<td>300 [13]</td>
<td>6000 [13]</td>
<td>N/A</td>
<td>4000</td>
</tr>
<tr>
<td>Lithium-sulfur</td>
<td>2</td>
<td>400–800</td>
<td>N/A</td>
<td>N/A</td>
<td>1400</td>
</tr>
<tr>
<td>Sodium-ion</td>
<td>1.7</td>
<td>800–800</td>
<td>1000–1200</td>
<td>N/A</td>
<td>500</td>
</tr>
<tr>
<td>Supercapacitor</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>10000–118</td>
</tr>
</tbody>
</table>

**IV. EXPERIMENTAL RESULTS**

This section describes the selection of power storage device and their corresponding charging and discharging tests. Furthermore, we present the measurements of read rate, brownout test, cold start time and read range tests in this section to both compare the performance of the H-WISP as well as demonstrate the successful realisation of a hybrid powered RFID sensor tag; the H-WISP.

**A. Power Storage Device Tests**

In real-world applications, it is common for the H-WISP to switch between charging and discharging states as the tag to reader antenna distance varies. Therefore, ability to recharging quickly while performing well under large number of charging and discharging cycles and at the same time having adequate capacity to maintain tag operations under the semi-passive mode are important features of a suitable Power Storage Device for the H-WISP. The other important parameters include self-discharge rate, energy and power densities, and nominal voltage. Self-discharge is important when the tag is not being used, and energy and power densities indicate the efficiency of the storage device. Having a high nominal voltage hinders the charging of the device with harvested power at a reasonable distance from a transmitting RFID reader antenna. Table I lists the properties of common rechargeable power storage technologies.

From Table I, we can see that although both lithium-ion polymer and thin film lithium batteries have high energy and power densities, and high charge/discharge cycles, their high nominal voltage (3.7 V) indicate that charging these batteries are problematic using the limited harvested energy. Both lithium-sulfur and sodium-ion batteries look promising, but they are under development and hence not commercially available [16], [14]. Nickel-cadmium batteries are limited by their high self-discharge rate, a charging problem commonly know as the “memory effect” that can subsequently shorten the lifespan of the battery and thermal runaway from over-charging leading to the destruction of batteries [8]. Nickel-metal hydride (NiMH) batteries have higher power density and charge/discharge cycles. NiMH batteries with low self-discharge rates (5%) are also available [9], [10]. Supercapacitors can also be regarded as a storage device with no constraints on nominal voltage and with extremely high power density and charge/discharge cycles [17]. Therefore, we ultimately considered NiMH batteries and supercapacitors as the main technologies for further evaluation.

As discussed in Section III, the EnerChip was regarded as the core of the HPMU along with the additional power storage device. The charging voltage and current will be determined...
by the EnerChip. The discharging condition is determined by the current draw at the fully active mode of the tag circuitry, which is around 250 µA [6] along with the onboard voltage regulator (minimum 1.7 V input voltage [19]) in the WISP. Therefore, the experiments are conducted using the simplified circuits shown in Fig. 6.

We used 6 mAh capacity NiMH batteries and 0.1 F supercapacitors to conduct our experiments. Due to the minimum voltage requirement for the voltage regulator and the nominal voltage of the NiMH batteries, one NiMH battery is insufficient to feed the voltage regulator and EnerChip, hence we arranged three NiMH batteries in series to test their performance. We tested 20 groups of batteries and capacitors and the experiment was repeated 20 times with each battery group and supercapacitor. It should be noted that during the NiMH battery test, we charged the battery from the starting point of approximately 10% discharge. The supercapacitors were charged from 3 V to 4 V as supercapacitors, strictly speaking, does not have a nominal voltage and hence tests were focused on discharging to a voltage above the minimum charging voltage, $V_{CHG}$ (see Fig. 3a) provided by the EnerChip. The charge and discharge characteristics were investigated under the assumption that the Power Storage Device will rarely be used and often remain almost fully charged with more opportunities for re-charging.

Figure 7 shows the charging and discharging curves for the supercapacitor and the NiMH battery. From this figure, we can observe that, as expected, the supercapacitor has a significantly faster charging time when compared with the NiMH battery. The capacitor sustained sufficient voltage for 5 minutes before dropping its voltage by 1 V. As expected NiMH batteries sustained their power for longer. It is important to note that the supercapacitor charge and discharge curves are consistent with virtually zero standard deviation.

The experiment results indicate that the supercapacitors are more suitable power storage devices for the H-WISP under the conditions we have considered due to its lower charging time and the ability to deliver consistently high performance over large number of charging and discharging cycles with a reasonably long period of power delivery albeit having less energy energy density than NiMH batteries (see Table I). Furthermore, physical size of the supercapacitor is significantly smaller than the stacked NiMH batteries, hence more suited for wide range of applications. Therefore, supercapacitor present itself as a very promising power storage device not only for the H-WISP, but also for other tags that require a power storage device.

B. Settings for the Performance Study

We obtained all the performance metrics using an Impinj Speedway R420 RFID reader operating in the frequency range from 920 MHz to 926 MHz under the Australian UHF ISM (industrial-scientific-medical) band for RFID.

In order to ensure the accuracy and repeatability of the measurements, all of the experiments are conducted under uniform environmental conditions where the WISP and H-WISP are sequentially placed in an anechoic box as shown in Fig. 8. During experiments, the reader antenna was at fixed position and the tag was placed along a dielectric rope with calibrations in 10 cm intervals using a holder. Tag communication was observed using the Impinj MultiReader (v6.6.10.240) software.
For the purpose of reducing power consumption caused by the onboard LED (see Section III-A), we used a prototype without the LED and instead modulated the tag ID to indicate the current state of the tag being either: i) charging; or ii) discharging during these experiments.

a) **Read rate:** This experiment was conducted by placing the tags inside the anechoic box at 1 m away from the antenna and varying the transmission power of the reader from 15 dBm to 30 dBm in steps of 1 dBm. The read rates of the WISP and H-WISP are shown in Fig. 9. It can be seen that the proposed H-WISP provides better overall read rates. The H-WISP could be read at the minimum 15 dBm while the WISP stopped responding at 19 dBm. This suggests that the H-WISP could be successfully read by the reader using a lower signal power and as a result, a longer reader range is expected. An interesting artefact of this investigation is the unusual read rate between 22 dBm to 27 dBm; we have attributed this to the finely tuned WISP front end with non-linear elements that are well matched to the antenna impedance under low power conditions.

b) **Brownout:** This experiment was conducted by placing the tags 1.2 m from the antenna inside the anechoic box. We set the reader transmitted power to 30 dBm and an anechoic obstacle is placed between the tag and the antenna at each time interval to simulate brownout events. The results of this experiments are shown in Fig. 10. As expected, read rates of the WISP and H-WISP with no interference were similar, but the deterioration of WISP read rate after each brownout event was much more significant than the H-WISP; a reduction in over 20 reads per second for the WISP compared to approximately 5 reads per second reduction for the H-WISP.

This results indicate that during brownout events, charged power storage device inside the H-WISP discarded to enhance the backscattered signal and thus perform better than the WISP. Moreover, this also implies that the H-WISP can successfully manage power as the initial read rate of the H-WISP being similar to that of WISP.

c) **Cold startup time:** In this experiment we measured the cold startup time of the WISP and H-WISP by varying the tag to antenna distance in the anechoic box at a fixed transmitted power 30 dBm. To obtain the startup time we utilized a regular passive RFID tag placed at the surface of the antenna as a reference tag. When the RFID reader started, the reference tag responds first and then the sensor tag responds. The time difference between the reading from the sensor tag and the reference tag is considered as the startup time. We initially place both tags (WISP and H-WISP) at 1 m distance from the antenna in order to accurately measure the startup time and changed the distance in steps of 10 cm.

From Fig. 11, it is clear that when the WISP is moved away from the RFID antenna, the startup time increases exponentially. In contrast, the H-WISP maintains a consistent startup time at varying distances. Therefore, the results indicate that when the incident RF power on the tag is insufficient, the power storage device in the H-WISP immediately provides power for the tag to commence its operations without having to wait for the power harvester to accumulate charges over time to eventually activate the tag (as in the case with the WISP).

d) **Range test:** Communication distance is an important factor for an RFID system. In this experiment, we recorded the harvested voltage and the regulated voltage of the H-WISP under fixed 30 dBm transmission power by varying the tag to antenna distance in an outdoor environment. Figure 12 shows the results we obtained. Here, we also show the 1 V and 2 V voltage thresholds used by the H-WISP to select the operating mode of the tag (see Section III and Fig. 1).

We can see in Fig. 12 that when the harvested voltage $V_{OUT} > 2\text{ V}$, the H-WISP performs similar to a WISP, however in contrast to a WISP, the power storage device in the H-WISP is also charged during this mode of operation. When the harvested voltage supply is between 1 V and 2 V, the storage device provides power for the H-WISP to function
The H-WISP is turned off when the harvested voltage drops below the 1 V threshold at approximately 6 m. Comparing with the WISP, which did not respond after the 2 V threshold which occurred at approximately 3 m according to our experiments, we can observe that the H-WISP has a longer operational range. The H-WISP provided continuous and consistent reads up to a distance of 6 m at which point the harvested voltage dropped below 1 V and the tag was turned off. The doubling of the operational range of the WISP from 3 m to approximately 6 m is a significant improvement.

V. EXAMPLE APPLICATIONS

To demonstrate the real-world application of the H-WISP, we selected two instances of an older person monitoring scenario. When passive sensors are used, there are limited sensor information on activities such as walking, and activity transitions such as stand-to-sit and sit-to-stand mainly because the sensor tag is not being able to harvest sufficient energy [7]. In these demonstrations, a normal WISP and the H-WISP were worn over the garment at the sternum level by a human participant as shown in Fig. 13a. Both tags were placed on top of 10 mm thick polystyrene isolators to remove interference from the human body and the reader transmit power was set to 30 dBm. This application demonstration was conducted in the environment illustrated in Fig. 13b.

First, we examined a scenario where a person is waking away from an RFID antenna. We measured the read rate of the tags as the participant moved away and the results are illustrated in Fig. 14. The WISP was not able to perform beyond 3.5 m, whereas the H-WISP was able to provide sensor information from a distance greater than 6 m and thus indicating that a person can be monitored at a longer distance. Performance of the H-WISP under activity transitions, particularly stand-to-sit and sit-to-stand are examined in the second scenario. Generally, limited sensor data from passive sensors during activity transitions forces researchers to identify activity transitions by identifying transitions between recognized activities [7]. For instance, a stand-to-sit transition is identified by first recognizing a standing activity and then recognizing a sitting activity. A chair was set up at a fixed position of 3.2 m from the reader antenna as shown in the Figure 13b. A participant, who was wearing both a WISP and a H-WISP was asked to stand in front of the chair and then sit down, and stand up from the chair. During this study, sensor data was recorded and annotated using an in-house developed data logging application.

Figure 15 shows the data collected for the stand-to-sit and sit-to-stand experiment. Here, we can clearly see that there are a small number of samples from the WISP compared to the H-WISP. Furthermore, it is important to note that during activity transitions the H-WISP captures more information to directly recognize activity transitions. This can be clearly observed during the sit-to-stand transition that occurred within $t = 20$ s.
and \( t = 22 \, \text{s} \) in Fig. 15.

These scenarios demonstrate that the H-WISP is indeed useful to address prevailing passive sensor related issues particularly with ubiquitous monitoring applications such as monitoring of the older people in hospital settings.

VI. RELATED WORKS

We developed the hardware and software components of the H-WISP based on the version of WISP 4.1DL with 3-axis accelerometer, temperature sensor and capacitance sensor [4]. The WISP 5.0, as a new version, is in development to optimize the energy consumption and increase the range of operation, notwithstanding the existing brownout problems are still relevant. Also the WISP 5.0 will provide the authors further opportunities to enhancement of the current HPMU.

Although the concept of hybrid power sources has not been looked at in the context of sensor tags to the best of our knowledge, researchers in [20] have proposed SolarWISP, which can harvest energy using a solar panel to achieve autonomous Computational RFIDs (CRFIDs). Having complementary power harvesting sources is also an effective approach [21] to the problems we have considered.

A hybrid tag proposed in [22] utilizes active and passive RFID circuits where the tag decides which circuit to be used depending on the ability to harvest energy. However, the use of a battery is always seen as a major limitation that constrains the operational life of the sensor tag and the type of application that it can be used in as these authors have not integrated the concept of wireless charging.

To the best of our knowledge, there are no ongoing research work on managing the brownout problem of passive sensor-enabled RFID tags by storing and actively managing harvested energy as proposed in this study.

VII. CONCLUSION AND FUTURE WORK

In this paper, we presented the design, implementation and evaluation of a hybrid powered RFID sensor tag; the H-WISP. H-WISP successfully addresses the problem of brownouts, which is more prominent in tags with on board sensors. From extensive evaluations we demonstrate that using the H-WISP, a higher read rate and a longer operational range can be achieved. We further demonstrated the usefulness of H-WISP in the context of activity recognition research using wearable devices. In future, we will improve the H-WISP by reducing the power consumption of the HPMU and consider new emerging power sources such as paper battery technologies.

VIII. ACKNOWLEDGEMENT

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