

A Battery-less BLE Smart Sensor for Room Occupancy Tracking Supplied by 2.45-GHz Wireless Power Transfer

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Abstract

Wireless power transfer (WPT) has emerged as a solution for supplying smart sensors for long-term battery-less deployment. Because the amount of power harvested by the smart sensor is limited due to WPT path loss, the optimization objective is twofold: achieving ultra-low-power operation for the sensing task and improving the harvesting efficiency even at low incident power. In this paper, we focus on the use case of a Bluetooth LE-connected motion detection system supplied by 2.45-GHz RF power. The full system (RF energy harvester, power management, sensor transducer and interface, control, data processing and wireless transmission) is implemented using low-power off-the-shelf components. In the sensing sub-system, ultra-low-power operation is achieved by the duty-cycling of the sensor interface and by an event-driven scheme for communication. In the harvesting sub-system, the design of the matching network and rectifier, combined with maximum power point tracking (MPPT), is optimized for increasing the power harvesting efficiency (PHE) at low incident power. Measurements show a total reduction in the power consumption for the sensing sub-system by a factor 20. When using custom WPT waveform with high peak-to-average power ratio, the RF energy harvester is functional with an incident RF power starting from -20 dBm. The smart sensor is able to perform its motion-detection task with an incident power as low as -17.3 dBm.

Keywords: RF energy harvesting, wireless power transfer, motion detection, ultra-low-power, smart sensors, wireless sensor networks, Internet-of-Things, room occupancy tracking, high-PAPR waveform

1. Introduction

In the context of the Internet of Things (IoT), the deployment of smart sensors in our environment is expected to skyrocket in the next few years, with estimated numbers rising up to several hundreds of billions of devices. Examples include air quality, light or temperature monitoring as well as occupancy tracking systems that may equip many smart homes and smart buildings in the near future.

In multistory buildings, because of the high number of sensors required for fine-grained monitoring of each room, the installation of the wiring infrastructure for such large distributed networks can induce high deployment costs. This cost can be avoided by relying on wireless solutions both for data transfer and power supply. For the communication aspect, wireless protocols designed for sensor systems are already widely used. Those exist for all sorts of applications, both low-power wide-area networks (LP-WAN, e.g. LoRa, SigFox, NB-IoT) or short-range networks (e.g. ZigBee/802.15.4, Bluetooth LE). In most cases, each smart sensor communicates with a shared gateway that can then transfer the smart sensor data to the cloud. Regarding the power supply, a straightforward solution is to supply the smart sensors with primary batteries but

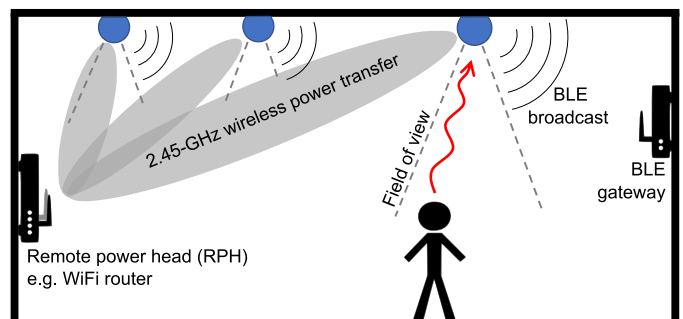


Figure 1: Wireless power transfer infrastructure in a room for fine-grained presence tracking. The smart sensors (in blue) harvest RF power, detect local motion via infrared light and use BLE to transmit information wirelessly.

this raises other issues in terms of maintenance (battery replacement) and environmental impact (battery ecotoxicity) [1]. Energy scavenging, that is, a way to continuously retrieve some energy from the environment to recharge a storage element, has been proposed as a solution [2]. However, achieving balance between the fluctuating scavenging power and consumed power in such system while maintaining sufficient quality of service (QoS) is a challenging task. Therefore, wireless power transfer (WPT) has emerged as an interesting alternative in spatially limited spaces, typically houses and buildings [3]. This solution can achieve

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cheap and large-scale deployment of battery-less IoT smart sensors, as it allows continuous power harvesting on the sensor side.

This paper is an extension of work originally presented at the Power and Timing Modeling, Optimization and Simulation 2018 conference (PATMOS 2018) [4]. The design of a WPT-supplied IoT smart sensor is studied with a focus on infrared motion detection for fine-grained room occupancy tracking which is a typical application of IoT in smart buildings. As shown in Fig. 1, changes in the amount of infrared light sensed in the sensor field of view are used to detect human presence. By placing several detectors inside a room, it is thus possible to track the room occupancy, that can then serve various purposes such as intruder detection or HVAC regulation. In order to trigger the action following a detected motion event, it is necessary to wirelessly transfer the data to a gateway. Among all existing communication protocols, Bluetooth Low Energy (BLE) is the most suitable as it is a short-range protocol that offers low energy per packet compared to LPWAN [5]. Companies such as Gooee, Enlighted or Thingsee already commercialize BLE-connected occupancy sensors for smart buildings, but their solutions require large batteries or a connection to electric mains [6, 7]. Finally, remote power heads (RPH) are required to transmit RF power towards the sensors. In order to avoid additional hardware, RPH can be embedded in existing infrastructure such as e.g. WiFi routers. Unfortunately, due to the equivalent isotropic radiated power (EIRP) regulations for the RPH and the WPT path loss, the incident RF power at the sensor side will be very limited and will decrease significantly with the distance between the RPH and the smart sensor due to path loss. In this paper, we thus focus on designing a battery-less WPT-supplied IoT smart sensor that requires minimum RF input power to ensure correct motion detection.

In this extended paper, in addition to describing more thoroughly some of the power budget aspects of WPT, we introduce and discuss the use of an acknowledgement mechanism for reliable BLE broadcasting. On the RF energy harvesting aspect, we also show that using custom waveforms with high peak-to-average power ratio (PAPR) can increase the harvesting efficiency at low incident RF power. Section 2 emphasizes the power design constraints by linking incident RF power, energy harvesting efficiency and power consumption aspects. In Section 3, we give an overview of the system architecture. Section 4 describes the design of the power management unit, including the selection of the storage element and of the system supply voltage. In Section 5, we detail the power optimization of the sensor interface thanks to duty-cycling. Section 6 proposes an event-driven BLE broadcasting scheme to reduce the number of transmitted packets while ensuring reliable communication. Section 7 shows the architecture of the RF energy harvester with emphasis on the relationship linking the different blocks to the overall efficiency of the harvesting sub-system with comparison to previous de-

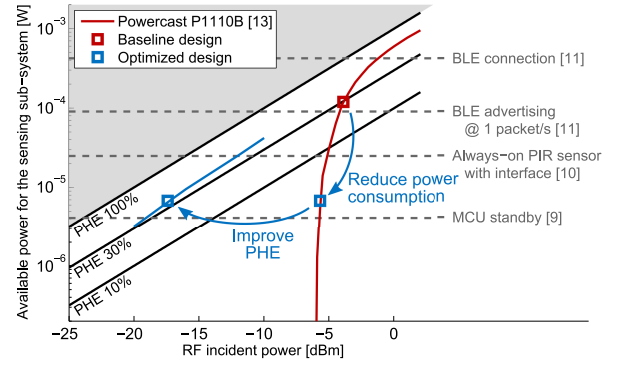


Figure 2: RF energy harvesting power budget. The power harvesting efficiency (PHE) links the RF incident power to the DC average power available for the sensing sub-system. Horizontal lines indicate typical power consumption related to the relevant tasks of our target system. Red data shows the performance achieved using existing baseline commercial components, while blue indications show a typical trajectory for the two-step optimization of the minimum incident RF power targeted in this paper.

signs. Prototype fabrication and system evaluation results are provided in Section 8.

2. Energy harvesting power budget

In a battery-less system, one needs to balance harvested power, resulting from the incident power from the environment and the efficiency of the harvester, with the required power needed to supply the platform. Indeed, as the incident RF power needs to be converted to a stable DC voltage to supply the sensing sub-system, power is lost in the RF energy harvester (RFEH) and the power management unit. The combination of incident RF power and harvesting efficiency thus sets the maximum average power that can be delivered to the system.

At the system level, the main figure of merit for which we want to optimize a WPT-supplied platform is the minimum incident RF power required to make the system functional. From the application point of view, this minimal amount of power will directly set the power level that needs to be transmitted by the remote power head and/or maximum distance to the smart sensor due to path loss. For example, in Europe, where the legal maximum emitting power of an RF source in the ISM band (2.45 GHz) is +24 dBm EIRP, a system that requires at least -15 dBm can handle a path loss up to 39 dBm. Using a directional antenna array, this roughly corresponds to a distance of 4-5 meters from the source in an unobstructed environment [8].

In order to compute the minimum incident RF power, we start by estimating the average power consumption of each task that must be performed by the sensing sub-system. This can be done either by using the technical documentation of the components, as shown in Fig 2 [9, 10, 11], or by direct measurement. Once the power

Table 1: Power budget of a baseline motion detection system.

Power consumption	119 μ W
MCU standby power	4 μ W
PIR sensor with interface	25 μ W
BLE adv. (1 packet/s)	90 μ W
Corresponding incident RF power	-3.9 dBm
Max. path loss (+24 dBm source)	27.9 dB
Estimated max. distance without obstacle	1.5 m

consumption of the sensing sub-system is known, the corresponding minimal RF incident power can then be obtained using the power harvesting efficiency (PHE) of the RFEH. This performance metric corresponds to the ratio between the input incident RF power and the average output DC power, which is also equal to the product of the power extraction efficiency and the power conversion efficiency (PCE) [12]. The PHE of an energy harvester always depends on the incident input power and frequency. In Fig. 2, the harvested power available for the system is given for different PHE levels. The PHE of a commercially-available RFEH, the P1110B from Powercast which is a single-package RF energy harvesting solution [13], is also shown. For a given energy harvester circuit, using the PHE versus incident power curve, it is possible to perform an injective mapping from the computed power consumption to the required incident RF power.

Table 1 shows the power budget for a baseline motion detection system implemented with the components identified in Fig 2 and powered with the Powercast P1110B. Before optimization, the estimated maximum distance from the source to the sensor system to provide enough power through WPT is limited to 1.5 m, which is not enough considering the targeted application.

In order to minimize the required incident RF power, the optimization objective is twofold: reducing the sensing power consumption and improving PHE, especially at low incident power. Indeed, reducing the power consumption for performing the task allows to shift the operation point along the PHE curve, as shown by the first blue arrow in Fig 2. However, at some point, the reduction in incident power is limited by the sensitivity of the harvester. To further reduce the incident power, we thus need to design an RFEH that provides higher PHE at low incident power (second arrow in Fig 2). Note that inversely, optimizing the RFEH alone, that is, without considering power consumption, is not enough to reach low incident power. Indeed, even considering an ideal PHE close to 100%, the power consumption of the system sets the minimal bound on the required incident power.

3. Smart sensor architecture

Fig. 3 shows the proposed architecture for the proposed battery-less motion detection sensor system and the

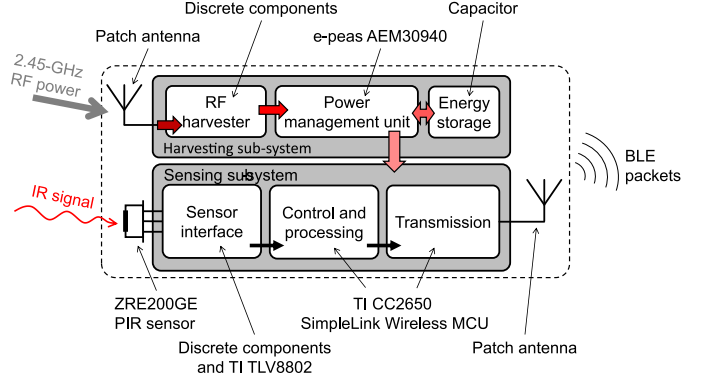


Figure 3: System architecture. The harvesting sub-system converts RF power to a stable supply voltage. The sensing sub-system uses this supply to perform the motion detection task. Commercially-available components used to implement the platform are indicated.

commercial components used to implement it. The harvesting sub-system interfaces the antenna and generates a regulated supply voltage for the sensing sub-system, which performs the motion detection from the infrared signals and transmits wirelessly the room occupancy information. In the harvesting sub-system, the RFEH harvests the RF power from an inverted-F patch antenna printed on the PCB and rectifies it to an unregulated DC voltage using discrete components. From this voltage, a power management unit (PMU) embedded in the AEM30940 chip from e-peas [14] generates the appropriate regulated supply voltage. The PMU also interfaces a capacitor that stores the excess energy when it is not immediately needed by the sensing sub-system, or provides excess power when the sensing sub-system consumes more power than harvested power. The sensing sub-system is composed of a passive infrared (PIR) transducer, ZRE200GE from Zilog [15], connected to a sensor interface. This analog interface built with TLV8802 ultra-low-power operational amplifiers from Texas Instrument [16] amplifies and filters the signal. A microcontroller (MCU) with embedded ADC digitizes this signal and then processes the acquired data to detect motion. When a motion event is detected, it triggers BLE transmission with a radio transceiver. In the proposed system, we selected the CC2650 from Texas Instrument [9], a wireless MCU combo with embedded BLE transceiver. Let us mention that local data processing on the smart sensor allows reducing the communication packet rate by only transmitting detected events instead of raw data, thereby significantly saving system power [17].

4. Power management

Smart power management is paramount for a system in which each μ W has its importance. Many modern commercial integrated circuits (IC) embed their own voltage converters. While this often simplifies the job of the system designer by offering a wider range of supply voltage, it also sometimes means that power conversion can be dis-

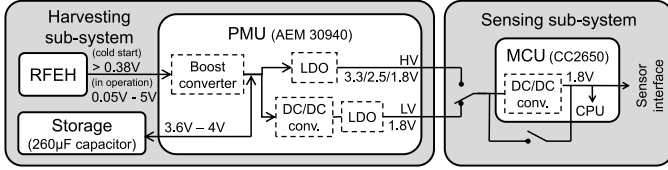


Figure 4: Schematic of the power management across harvesting and sensing sub-systems. The DC output voltage of the RFEH is boosted to charge the SuperCap. Two paths (HV and LV) allow generating appropriate supply voltage to the sensing sub-system. The DC/DC converter of the MCU converts the voltage to 1.8V if necessary.

tributed among several redundant stages in a way that may not be the most efficient. In this section, we explain and quantify how power is converted from the RFEH output to the sensing sub-system supply through the power management unit and storage element. It is the opportunity to show how thorough evaluation of the efficiency of each block present in the PMU can help choosing the most appropriate supply strategy. The choice of the storage element is also discussed.

Fig. 4 shows the power management schematic across harvesting and sensing sub-systems. The power management unit (PMU) extracts power from the low unregulated RFEH output voltage and slowly charges an energy storage element, both using an input/output voltage regulated boost converter. The stored energy is then converted to a stable voltage for supplying the sensing sub-system. The AEM can be configured to accommodate for different storage element types (Li-Ion battery, thin-film battery, super- or conventional capacitor) and generate various supply voltages (1.8, 2.5 or 3.3 V). Two different paths can be used to provide the supply voltage : High Voltage (HV) with a single low-dropout (LDO) regulator, or Low Voltage (LV) with a DC/DC converter and an LDO regulator. The selected MCU (CC2650) also has an internal DC/DC converter that allows operation between 1.8 and 3.8 V. At 1.8 V, it is more efficient to by-pass this converter [9].

In order to choose the best configuration for the power management across the PMU and the MCU, it is necessary to take into account the conversion efficiency of the different stages. Figure 5 shows the power losses in four different configurations. The total height of each bar corresponds to the input harvested power provided by the RFEH, while the white part corresponds to a given $30 \mu W$ load, consumed by the sensing sub-system at 1.8 V. As the power efficiency of individual blocks inside an IC is rarely provided by the manufacturer, this data often needs to be measured. From this graph, we see that the most efficient configuration is when the AEM30940 PMU directly provides a supply voltage of 1.8 V through the LV path, and the DC/DC converter of the MCU is therefore disconnected, allowing to gain 12% of efficiency compared to the default configuration (Config. A). It is also the solution that minimizes the drop-out on all low-dropout regulators (LDO) in the conversion path.

For the selection of the energy storage element, several

Table 2: Characteristics of storage element types [19, 20].

	Li-Ion battery	SuperCap	Ceramic capacitor
Energy density [Wh/kg]	10-100	1-10	< 0.1
Lifetime [years]	3-5	> 10	> 25
Max. charge cycles	500-2000	> 500000	$\approx$ unlimited
Leakage current	> $5 \mu A$	> 500 nA	[1-100] nA/ μF

factors need to be taken into account: lifetime, energy capacity, number of charge cycles and self-discharge rate (see Table 2). Because of their limited lifetime and maximum number of charge cycles, most chemical batteries, such as Lithium-Ion are not suited for this application. Two alternative options are the conventional ceramic capacitor or the super-capacitor (SuperCap). Ceramic capacitors offer many advantages, in particular an excellent stability over time and charging cycles which is very suitable for devices designed to last several decades. Their main disadvantage however is their leakage current that slowly discharges the capacitor, which can be quite high depending on the size and type of capacitor. This leakage adds up to the power consumption of the sensing sub-system as it needs to be supplied by the RFEH. On the other hand, SuperCaps tend to show lower leakage currents relative to their capacitance but suffer more from ageing effects (namely reduction of capacitance and increase of equivalent series resistance and self-discharge) [18]. However, as the capacitance of commercially-available SuperCaps are usually much higher than ceramic capacitors, they rarely show leakage currents lower than $1 \mu A$. We have decided to work with conventional ceramic capacitors for their stability, keeping in mind that their size should be limited to avoid power losses through self-discharge. If the capacitance is chosen in the μF range, it is possible to find capacitors with an insulation resistance in the $M\Omega$ range, which equates to leakage power of a few tens of nW, thus well below the actual power consumption of the sensing sub-system.

The capacitance value needs to be chosen so that the capacitor can tolerate the most energy-demanding tasks while keeping a voltage that is high enough for the power management unit. The task that requires the most energy over a short period is the BLE transmission. As will be described in Section 6, when the maximum number of trials is set to 5, the maximum amount of energy that must be provided by the energy storage unit for a single packet is $200 \mu J$. The capacitor should therefore be able to provide $400 \mu J$ in the worst case (when 2 events occur successively) when the voltage drops from 4 V, which is the rated voltage limit set by the AEM30940 PMU on the storage element, to 3.6 V, which is the minimum voltage

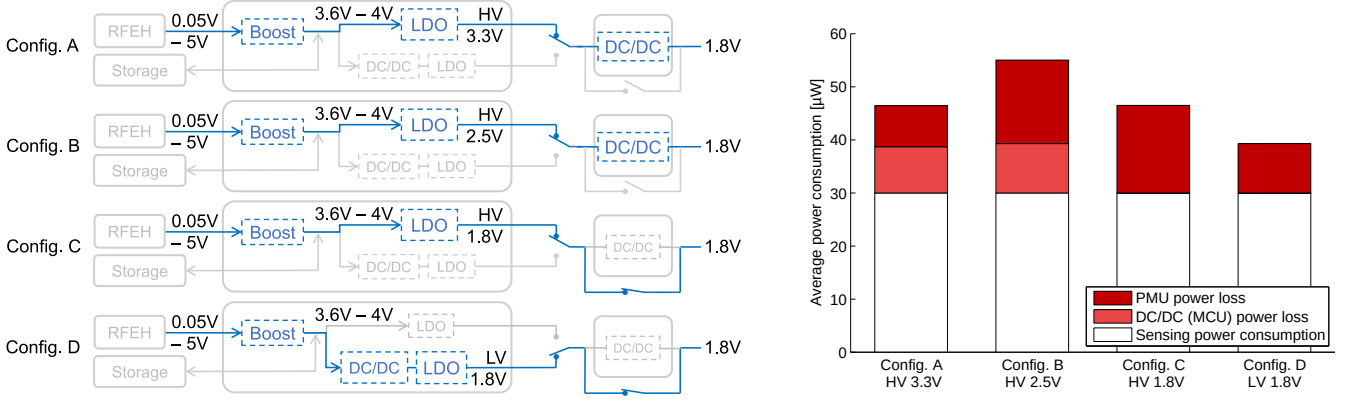


Figure 5: Four possible power management configurations (left) and measured associated power consumption (right). On this bar chart, the total height corresponds to the input power from the RFEH and the red parts depicts the power management losses for a given load of $30 \mu\text{W}$ in white, as a function of the chosen power management configuration.

in its default configuration. Using

$$\Delta E = \frac{1}{2} C_{store} (V_{high}^2 - V_{low}^2)$$

where ΔE is the energy available from a capacitor with capacitance C_{store} when changing from a voltage V_{high} to a voltage V_{low} , we get that the capacitance of the storage element should be above $260 \mu\text{F}$.

5. Sensor interface

The sensor interface performs the conditioning of the signal from the PIR sensor. This signal is then sampled and processed to detect motion events. Fig. 6 shows the schematic of the sensor interface along with parts of the CC2650 wireless MCU involved in the control and processing of the signal.

The CC2650 MCU must periodically sample the analog sensor signal, process the data and control the wireless communication. To this end, we use the real-time clock (RTC) to wake up the sensor controller every 1 second, which triggers a digitization operation by the ADC. The sensor controller is a low-power co-processor embedded in the CC2650 MCU designed for efficient peripheral management. As this co-processor is capable of performing basic mathematical tasks, we also use it for simple motion detection by comparing the difference between two successive samples with a pre-defined threshold. If motion is detected, an interrupt request (IRQ) is sent to the CPU (Cortex-M3), which then triggers a BLE event packet transmission.

As proposed in the datasheet of the PIR sensor [15] and in the application note [10] from Texas Instruments, we use a band-pass amplifier circuit built around an operational amplifier as shown in Fig. 6 in black. The TLV8802 amplifier [16] has been chosen for its ultra-low power consumption. The output of the amplifier is connected to the ADC input of the CC2650 MCU for digitization.

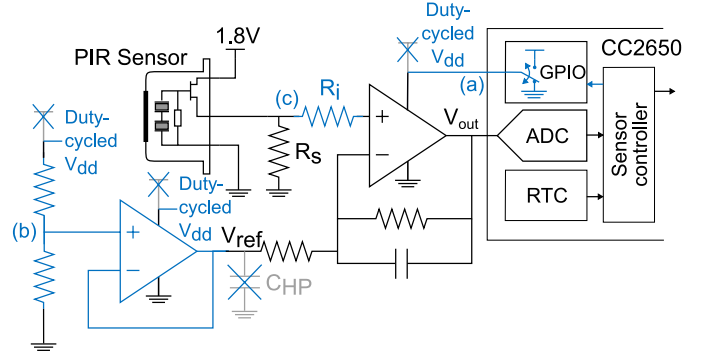


Figure 6: Schematic of the sensing sub-system. Changes made for duty-cycling the sensor interface are highlighted in blue : GPIO supply switching (a), voltage reference (b) and amplifier input resistance (c).

The following sub-sections detail how we achieve ultra-low-power operation to meet the low power budget set by the energy harvester. In addition to 1.8 V operation discussed in the previous section, several solutions will be studied and experimentally quantified. Firstly, duty-cycling of the sensor interface allows to significantly reduce the power consumed by the sensor interface. While this technique is often applied to integrated circuits, additional challenges of its use in circuits with discrete components will be discussed. A second improvement is the reduction of the PIR sensor biasing current while limiting the impact on the sensitivity.

5.1. Analog interface duty-cycling

One approach for the reduction of power consumption is the power duty-cycling. This consists in switching back and forth between an active mode that allows to perform the task but consumes a large amount of power and a low-power sleep mode in which no operation is possible. The objective is to perform the task as quickly as possible to limit the time in active mode and save power in sleep mode. Thanks to its general purpose input/output (GPIO) pins

with high-drive capability (4 or 8 mA), the sensor transducer and sensor interface can be powered directly from the CC2650 and therefore duty-cycling can be applied as shown in Fig. 6(a). The main constraint in applying this technique is the time required to switch from one mode to the other. In this analog circuit, this wake-up time is mainly due to the charge and settling time of nodes in the circuit. The most critical timings are the charge of the high-pass capacitor C_{HP} , the start time of the operational amplifier and the settling time of the sensor.

The charge time of the capacitor is proportional to the inverse of its cut-off frequency. Because the signal of the PIR has a low frequency (between 0.5 and 5 Hz), the charge time is on the order of 1 second. Considering a sampling frequency of 1 S/s, the power reduction offered by duty-cycling with such a long charge time is not interesting. A solution is to replace this high-pass capacitor by a voltage reference (V_{ref}) set as close as possible to the DC voltage at the output of the PIR sensor. The voltage reference is built using a voltage divider and a voltage follower amplifier (Fig 6(b)). This solution works as long as the difference between those two voltages multiplied by the gain of the amplifier stays within the saturation limits. According to our measurements, a maximum difference (including resistor precision, temperature and illumination variations and device-to-device variations) smaller than 30 mV is observed. Considering a dynamic output voltage range of 1.8 V, this allows for an amplifier gain up to 60 V/V to avoid saturation. As the range of variations on the sensor output is around 1 mV and the resolution of the ADC is 2 mV, this gain is large enough. Because of the resistive voltage divider, this voltage reference circuit consumes 4 μ W of power when active, which can be further reduced by increasing the resistance. However, duty-cycling makes it negligible in the total power consumption.

The starting time of the operational amplifier has been measured to be 4.5 ms, as shown in Fig. 7. Before this period, the output of the interface does not provide any information on the sensor state. This therefore sets a limit on the minimum active time period and on the minimum duty-cycle percentage. The settling time of the PIR sensor is about 30 seconds which is too long to consider duty-cycling. The sensor therefore has to stay powered on at all times. In order to limit its continuous power consumption, we have to increase the biasing resistance R_s as will be discussed in Section 5.2.

One additional problem that occurs when the power of the TLV8802 amplifier is cut off is that it loses its high impedance at the input pins, e.g. due to ESD protection devices. This means that the source resistance found in Section 5.2 is significantly reduced and the current increases to 2 μ A. This can be solved by simply adding a large series resistance R_i of 8 M Ω as depicted in Fig. 6(c). This has no impact on the gain or signal-to-noise ratio (SNR) of the amplifier circuit during operation but limits the current when the amplifier is shut off.

The sensor interface can therefore be duty-cycled with

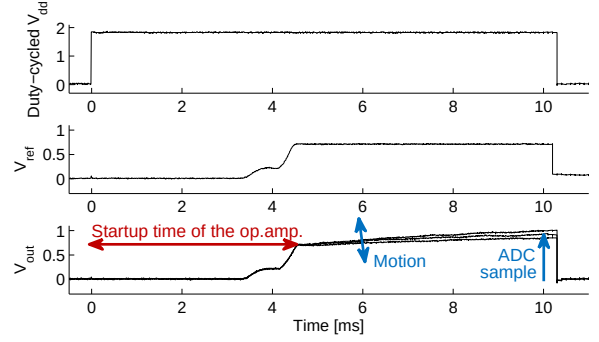


Figure 7: Measured sensing sub-system signals when duty-cycling the sensor interface. Output voltages of the amplifiers (V_{ref} and V_{out}) require 4.5 ms to stabilize (startup time). Traces of the amplifier output for different samples are superimposed to show the effect of motion on the signal.

an active period of 10 ms every 1 s. With a power consumption in active mode and in shutdown mode of 5.5 μ W and 180 nW respectively, the average duty-cycled power is 235 nW. Unfortunately, duty-cycling the sensor interface also comes at the cost of waking up the sensor controller twice: once to activate the supply via the GPIO, and once to sample the data and turn off the GPIO. This increases the average power by 290 nW for a total of 0.525 μ W, which still pays back significantly when compared to the active mode power of 5.5 μ W.

5.2. PIR sensor power-performance optimization

The part of the sensing sub-system that consumes most of the power is the PIR sensor. This power consumption can be modified by changing the R_s bias resistance connected between the source of the sensor and the ground. In order to avoid degrading the sensing performance and find an optimal resistance, we measured the power consumption and output SNR of the sensor for various source resistance values (see Fig. 8). When increasing the resistance value, the power is dramatically decreased. Meanwhile, the impact on the SNR is limited and it still allows to perform the motion detection with few false positive events as extreme noise values exceeding signal amplitude are very rare. A more in-depth analytical understanding of the impact of R_s on the SNR is difficult due to the lack of a proper model for the sensor. The resistance value is chosen as 8 M Ω , much higher than the value suggested in the datasheet (47 k Ω), so that the PIR power becomes negligible in the total power consumption.

6. BLE transmission

Wireless transmission represents a significant part of the total power consumption. Bluetooth LE offers different communication modes, of which broadcasting is the one that is the most suited for sensor systems with very low datarates. BLE broadcasting consists in sending data periodically at a chosen advertising interval in dedicated

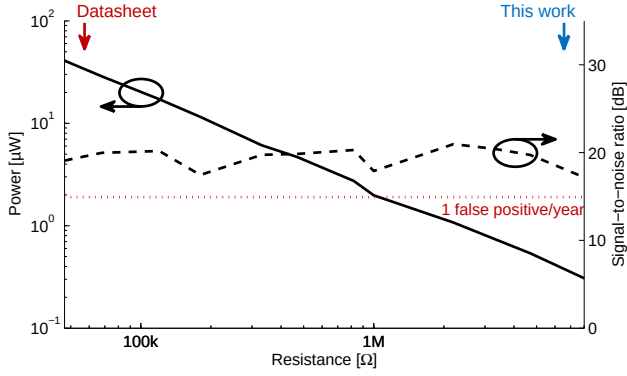


Figure 8: Measured power consumption of the PIR sensor [15] and output signal-to-noise ratio for different values of resistance between the source of the sensor and the ground. The SNR threshold shows the theoretical minimum for observing less than one false positive per year.

channels (usually 3), not knowing if other devices are listening. While we can consider that the energy per packet is fixed, there are ways to modify this communication scheme to reduce the number of transmitted packets, and therefore the average power consumption. The naive solution of increasing the advertising interval can be implemented easily but comes at the cost of a proportional increase in latency of the response to a motion. In order to solve this issue, we use event-driven broadcasting and we introduce an acknowledgement mechanism, as described in the following subsections.

6.1. Event-driven broadcasting

Generally speaking, broadcasting data periodically has the disadvantage of consuming large amounts of energy recurrently during the transmissions even if nothing happens in the sensor signal as shown in Fig. 9. To avoid this, an alternative strategy is to process the data locally and broadcast an information packet asynchronously only when an event is detected [17]. In the motion detection case, there are two events: motion start and motion end, which indicate that room occupancy changes. In this case, the average power consumption can be kept at a minimum when nothing happens. However, the maximum average power consumption that we need to take into account in the power budget is when there is frequent occupancy changes in the sensor field of view. To avoid transmitting nearly every second in such a case, we can define the event corresponding to the end of motion as when no motion was observed for a given back-off period, e.g. 10 seconds as illustrated in Fig. 9. This allows to limit the maximum transmission rate to 2 packets for every back-off period, while keeping short latency when new events occur. The disadvantage is that occupancy changes that are closer in time than the selected back-off period cannot be distinguished, but this has little impact in the foreseen applications. For example, applications such as HVAC regulation

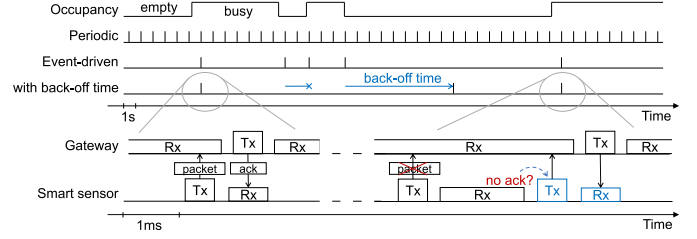


Figure 9: BLE broadcasting strategies. The top graphs show the behavior of a broadcasting strategy in response to an occupancy stimulus, for periodic broadcasting and event-driven broadcasting, with and without back-off time. Each vertical bar corresponds to a BLE packet transfer. The bottom graph shows the operation modes and data transfer between the sensor system and the gateway when using the acknowledgement mechanism.

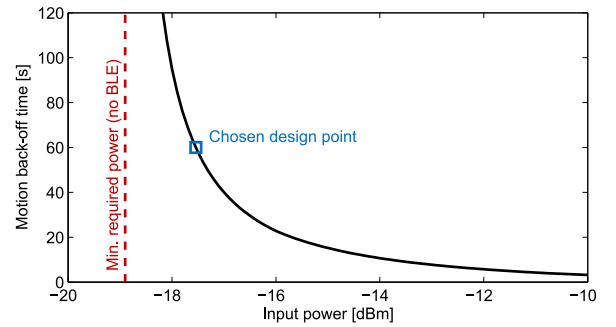


Figure 10: Trade-off between input power and motion event duration.

or surveillance rarely require a resolution for the end of an event finer than one minute.

Choosing a longer back-off time thus limits the number of transmissions but reduces the ability to distinguish occupancy changes that are closer in time. The minimum back-off period, which allows meeting the power budget, can be found based on the available power from the energy harvester ($P_{harvest}$), the average power consumed by the sensing sub-system when no motion is observed (P_{sense}) and the average energy required for the transmission of an event packet (E_{packet}). Using those parameters, the minimum blackout period to select is :

$$T = \frac{2 \times E_{packet}}{P_{harvest} - P_{sense}}.$$

The denominator of the fraction can be understood as the power available for transmission after removing the average sensing power. The factor 2 is due to the fact that 2 packets can be sent consecutively if a new motion starts just after the end of the previous blackout period. Figure 10 shows the trade-off between the incident RF power and the minimum back-off period. The red dashed line represents the minimum incident power required to make the sensing sub-system work. In this implementation, we choose a back-off period of 1 minute which allows to significantly reduce the power consumption without adversely impacting the targeted applications.

6.2. Acknowledgement mechanism

One disadvantage of the proposed event-driven broadcasting scheme compared to periodic broadcasting is the loss of redundancy that can affect reliability. With periodic broadcasting, if the transmission of a packet fails (e.g. in case of strong interference), the time before sending a new packet is short and only latency is affected when an event is detected. On the other hand, for event-driven broadcasting, if the transmission of a packet fails, information is completely lost as it will not be sent again until a next event occurs.

One solution to improve reliability is to implement an acknowledgement mechanism to ensure correct transmission of the data packet. As illustrated in Fig. 9, once the packet is received by the gateway, it sends an acknowledgement packet back to the smart sensor. If the sensor does not receive the answer from the gateway, it repeats the transmission again with a predefined maximum number of trials. The price to pay for this mechanism is an increase in energy due to the reception of the acknowledgement and the potential additional trials. To mitigate this increase, the number of broadcasting channels is reduced from three to one. The average energy per packet E_{packet} , depending on the number of trials N , is:

$$E_{packet}(N) = E_{init} + \sum_{n=0}^{N-1} (1 - \text{PER})^n (\text{PER} \cdot E_s + (1 - \text{PER}) \cdot E_f)$$

where E_{init} is the energy for initializing the radio, E_f (E_s) is the energy for a failed (succeeded) trial and PER is the packet error rate of a single trial. Note that the difference between E_s and E_f is linked to the small difference of time spent in receiver mode, as the receiver either stops when a message is received or stays active during a given listening time. Experimental measurements data for a packet length of 14 bytes shows a BLE transmission duration of 0.5 ms and a typical gateway response latency of 1 ms. Fig. 11 shows the performance of the acknowledgement mechanism compared to the single transmission depending on the success rate of a single packet transmission, for different numbers of trials. The success rate for a single transmission measured in a typical office environment was 96 % with a 5 m distance between the sensor system and the gateway. With a choice of 5 trials maximum, this translates to a mean time between errors of more than 25 years for an average energy per packet of 50 μJ . Note that in order to perform multiple trials, enough energy must have been stored in advance. For the capacitor sizing discussed in Section 4, the maximum stored energy is related to the maximum energy consumption (when all packets fail) and not the average energy.

7. WPT RF energy harvester

The power transferred wirelessly from the RPH to the motion-detection smart sensor is harvested from an antenna by the RFEH

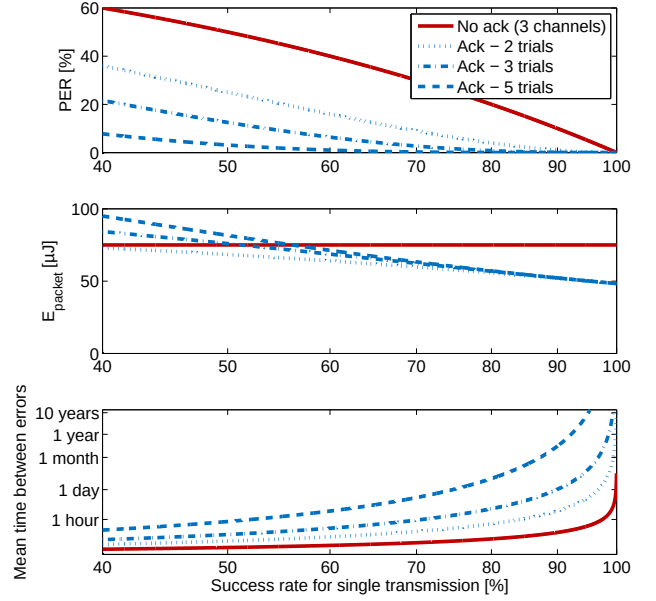


Figure 11: Performance of BLE acknowledgement mechanism on 1 channel (in blue) compared to conventional scheme on 3 channels (in red).

In the harvesting sub-system, the RF energy harvester (RFEH) collects the incident AC electromagnetic power and converts it into a DC electrical power to charge the storage element. A typical RFEH is composed of an antenna, an impedance matching network, an AC/DC rectifier and an energy-storage manager. The role of the matching network is to match the input impedance of the rectifier to the antenna impedance, usually 50 or 75 Ω . The total power harvesting efficiency (PHE) results from the power losses in these 3 stages. As illustrated in Fig. 12, four main sources of RF power losses in RFEH subsystem are to be considered: RF power reflected due to impedance mismatch, power loss in the matching network, power loss in the AC/DC rectifier and power loss in the storage charger. Therefore, the PHE can be formulated as:

$$PHE = PEE \times PCE$$

with $PCE = \eta_{MN} \times \eta_{REC} \times \eta_{SC}$

where PEE is the power extraction efficiency, namely the ratio between the power transmitted to the matching network and the RF incident power, and PCE is the global power conversion efficiency, equal to the conversion efficiency of each block.

This section first discusses the RFEH design with the PHE limitation at low incident power. The use of custom WPT waveform with high peak-to-average power ratio (PAPR) waveforms is discussed as a solution to this problem.

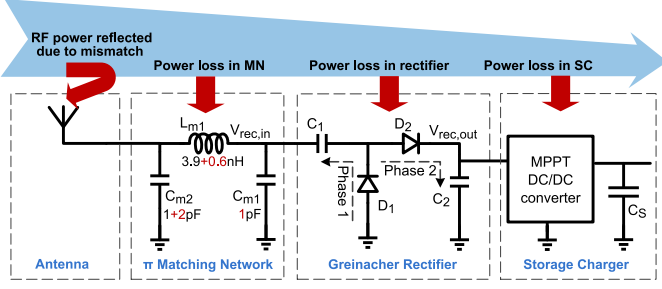


Figure 12: Schematic of the proposed RFEH sub-system. The arrow at the top shows the power losses occurring in the different stages. Inductance and capacitance values in red in the matching network are contributed by PCB and package parasitics.

7.1. Proposed RFEH

As shown in Fig. 12, the proposed RFEH is based on a receiver patch antenna printed on the PCB, a π matching network, a Greinacher rectifier and a storage-charging DC/DC converter embedded in the AEM30940 PMU, performing maximum power point tracking (MPPT).

Compared to the two-element L matching networks for which the quality factor Q is set by the source and load impedance, the three-element π network overcomes this disadvantage and can be used for narrow-band high- Q applications [21]. Additionally, tuning the C_{m2} capacitance in the π matching network can be used to compensate for the parasitic capacitance of the rectifier diodes. The Greinacher doubler circuit schematic is represented in Fig. 12. During Phase 1, when the AC input voltage $V_{REC,in}$ is below the ground level and its absolute value is larger than the threshold voltage V_t of the diode D_1 , a forward current is generated and flows from the ground to the matching network. The charges accumulate on capacitor C_1 . During Phase 2, when the AC input voltage $V_{REC,in}$ is above the ground level and its absolute value is larger than the V_t of D_2 , the diode D_1 turns off and D_2 turns on. The forward current flows from the input capacitor C_1 through the output diode D_2 to the output filter capacitor C_2 .

To size the matching network, we need to consider fixed input/output impedances. However, the rectifier input impedance varies with $V_{REC,in}$, which depends on the incident RF power. Therefore, the matching network efficiency significantly decreases at low incident RF power, when the rectifier impedance diverges from its nominal value. In this design, because of the 2.45 GHz operation, the matching network is sized at low rectifier impedance with moderate incident RF power (-5 dBm), because both the diode and PCB parasitic capacitors add up to C_{m1} and make the matching network hard to size at lower RF incident power with high rectifier impedance [22]. Figure 13 shows the increase in the power losses, in particular for reflected power due to impedance mismatch, when the incident power diverges from its nominal value.

The output voltage of Greinacher rectifier $V_{REC,out}$ can also influence its impedance and have further effect

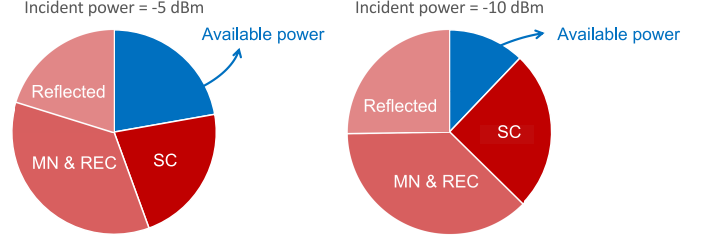


Figure 13: RFEH power losses. The red part shows the distribution of the power losses in each stage of the RFEH. The blue part is the remaining power transferred to the storage element and available for performing the task.

on PHE, as shown in Fig. 14. By regulating the rectifier output voltage $V_{REC,out}$ with MPPT as done by the AEM30940 PMU, $V_{REC,out}$ is forced to be at a certain ratio of its open load output voltage to track the maximum PHE. This technique is sometimes referred as pseudo MPPT [23] or fractional open circuit voltage MPPT (FOCV-MPPT) [24]. The optimum FOCV-MPPT ratio for the proposed RFEH is close to 40%. Among the three MPPT ratios that can be selected with the AEM30940 (50, 70 or 85%), a ratio of 50% offers the best PHE. This can be explained by the fact that the rectifier impedance is lower with a lower rectifier output voltage $V_{REC,out}$.

The measured PHE for the proposed RFEH with a single-tone input waveform is shown in Fig. 15. Despite its slightly reduced PHE at high incident power (close to 0 dBm) which is due to a reduced impact of parasitics for Powercast at sub-GHz operation [22], the sensitivity of the proposed 2.45 GHz RFEH reaches much lower incident RF power compared with its commercial counterpart. It therefore allows to provide the required sensing power at a much lower incident power, as illustrated in Fig. 15. Since this work uses discrete components featuring a lower threshold voltage than transistors in CMOS integrated circuits, it shows a slightly lower PHE compared to research state-of-the-art. Additionally, [25], [26] and [27] are only simulation results. [26] only takes the rectifier efficiency into consideration.

7.2. High peak-to-average power ratio

In the previous section, Fig. 14 showed that higher PHE is reached at higher incident power due to higher rectifier input voltage and thus lower input impedance, which is easier to match with the matching network. However, due to EIRP regulations, the remote power head (RPH) has a limited average output power.

In order to alleviate this limitation, we can use custom WPT waveforms with a non constant envelope in order to achieve short high-power WPT bursts, while keeping the average RPH output power below the EIRP regulation limit. Such custom waveforms are usually referred to as high-PAPR waveforms and can be generated by e.g. combining multiple tones [28]. In this work, we generated the high-PAPR WPT waveform shown in Fig. 16 by using

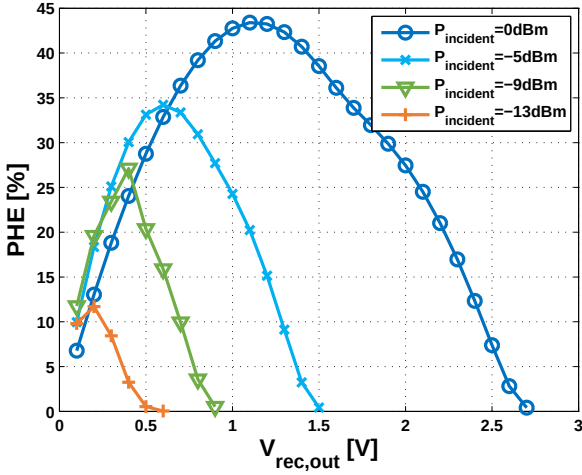


Figure 14: PHE vs. $V_{rec,out}$ at different RF incident power.

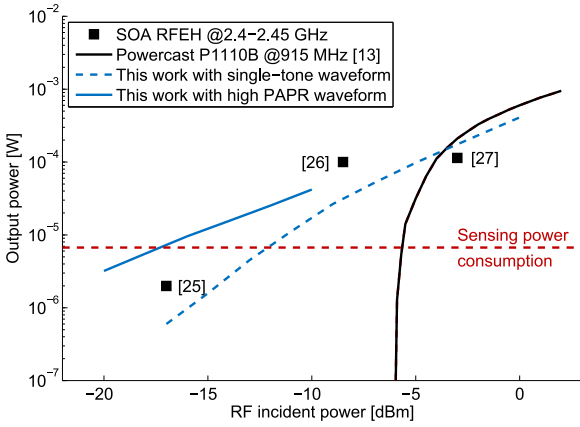


Figure 15: Comparison between the proposed RFEH, a commercially-available RF energy harvesting solution and designs from the literature [25, 26, 27]. The red dashed line corresponds to the power required to supply the sensing sub-system, after optimization.

64 BPSK-modulated tones for a total 3-MHz fitted in two 2-MHz adjacent BLE channels, that we allocate to WPT. It reaches a maximum achievable PAPR of 18.24dB with a periodicity of 21 μ s. The peak-to-average power ratio (PAPR) is defined as the peak amplitude squared (equal to the peak power) divided by the RMS amplitude squared (equal to the average power).

When using such high-PAPR waveforms, the RFEH benefits from its improved PHE, normally observed at higher incident RF power with single tone waveforms, even though the average RF incident power is low. Fig. 15 shows that the measured output power, and hence the PHE as well, is indeed boosted, in particularly at low average incident power. The downside of high PAPR waveforms is that they require a more complex remote power head design with a lower power amplifier (PA) efficiency ($P_{out,TX}/P_{PA}$) due to the non-constant envelope, unless

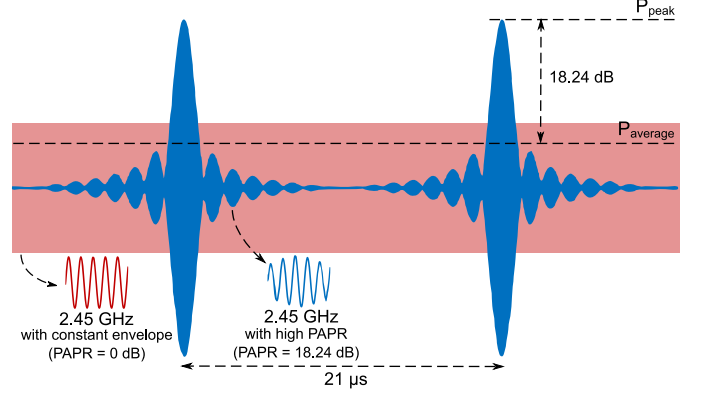


Figure 16: Example RF incident high-PAPR waveform (blue) with 18.24 dB PAPR and 21 μ s between peaks, compared to single-tone waveform (red). Both waveforms have the same average power.

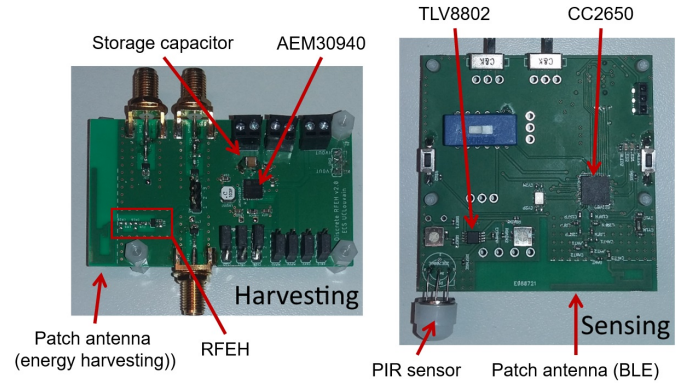


Figure 17: Stackable PCBs for harvesting sub-system (left) and sensing sub-system (right). Unlabeled components were used for board configurability and measurements.

an envelope-tracking PA is used [29].

8. Prototyping and system evaluation

Both harvesting and sensing sub-systems were prototyped in separate stacked PCBs shown in Fig. 17. Without high PAPR, the whole system was tested using a 50- Ω RF generator (Synthe MXG N5181A) connected with an SMA cable as input power source to characterize the minimum RF input power to ensure correct motion detection. High PAPR was tested using National Instrument USRP devices as RF waveform generator. While the RFEH requires a short initial burst of power at 0 dBm to cold-start the AEM30940 PMU, it can operate alone in regime with an incident RF power as low as -20 dBm with high PAPR waveforms.

The main measured performance metrics are listed in Table 3. Because of the event-driven broadcasting, the actual power consumption of the sensing sub-system, and thus the required RF incident power, depends on the sensed data. The power consumption of the sensing sub-system is 4.3 μ W when there is no motion. By selecting a motion back-off period of 1 minute, the worst-case average power

Table 3: Measured performance results.

Min. RF incident power (without motion)	-19 dBm
Min. RF incident power (with 60 events / hour)	-17.3 dBm
Average power consumption	[4.3 - 6.8] μ W
Average BLE transmission energy per packet	50 μ J
Maximum motion detection distance	4 m
Motion detection false alarm rate	< 0.06 / hour

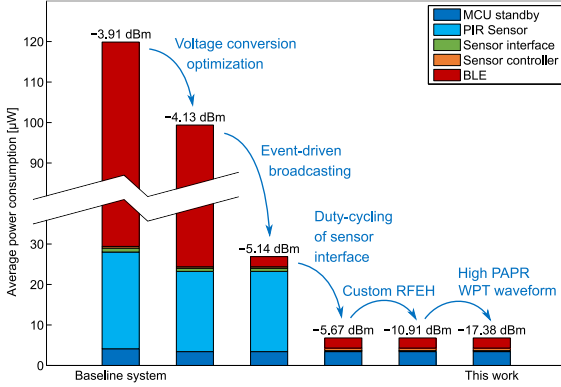


Figure 18: Successive system optimization steps. Each bar corresponds to the power consumption of the sensing sub-system at some stage of the optimization. The numbers on top of each bar represent the minimum required incident RF power.

consumption is limited to 6.8 μ W and the continuous operation of the smart sensor is possible down to -17.3 dBm of RF power incident to the RFEH. Using a +24 dBm RF source with directional antenna array, the system can handle a path loss up to 41.3 dB, which corresponds to an estimated distance of 6 m, thereby enabling the targeted application. Motion detection performance results shown in Table 3 indicate that the sensing task is performed properly.

9. Conclusion

This paper investigated how to meet the power constraints set by the battery-less WPT operation of a motion detection smart sensor. In this system, it has been achieved by combining ultra-low-power consumption of the sensing sub-system and the implementation of an RFEH with decent PHE at lower incident power as shown in Fig 18. The power consumption of the sensing sub-system has been reduced by 20 $\times$ thanks to several optimizations in the different blocks. Evaluation of the voltage conversion allows to save 20 μ W, i.e. an efficiency increase of 12%. Duty-cycling of the sensor sub-system and reduction of the PIR sensor power consumption saved 20 μ W. Additionally, event-driven broadcasting, made reliable thanks to the acknowledgement mechanism, provided an additional

decrease of 74 μ W by reducing the wireless communication power by 30 $\times$ without impacting latency. Regarding the RF energy harvesting, power-aware sizing of the circuit achieves higher PHE at low incident power by taking into account all power losses in the blocks, which allows to reduce the required RF incident power by -5.2 dBm. Finally, using high-PAPR waveforms provides an additional gain of 6.5 dBm, setting the required incident power to -17.4 dBm.

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