Battery-Less RFID-Based Wireless Sensors

Subjects: Engineering, Electrical & Electronic

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Wireless sensors are becoming increasingly popular in the home and industrial sectors and are used for a range of applications, from temperature or humidity monitoring to food-quality inspection of products being sold on the market. One of the main reasons for using wireless technology is that it affords non-contact, non-invasive sensing. This ability eliminates the need for long cables required for information transfer and reduces the spread of germs and brings comfort to the users.

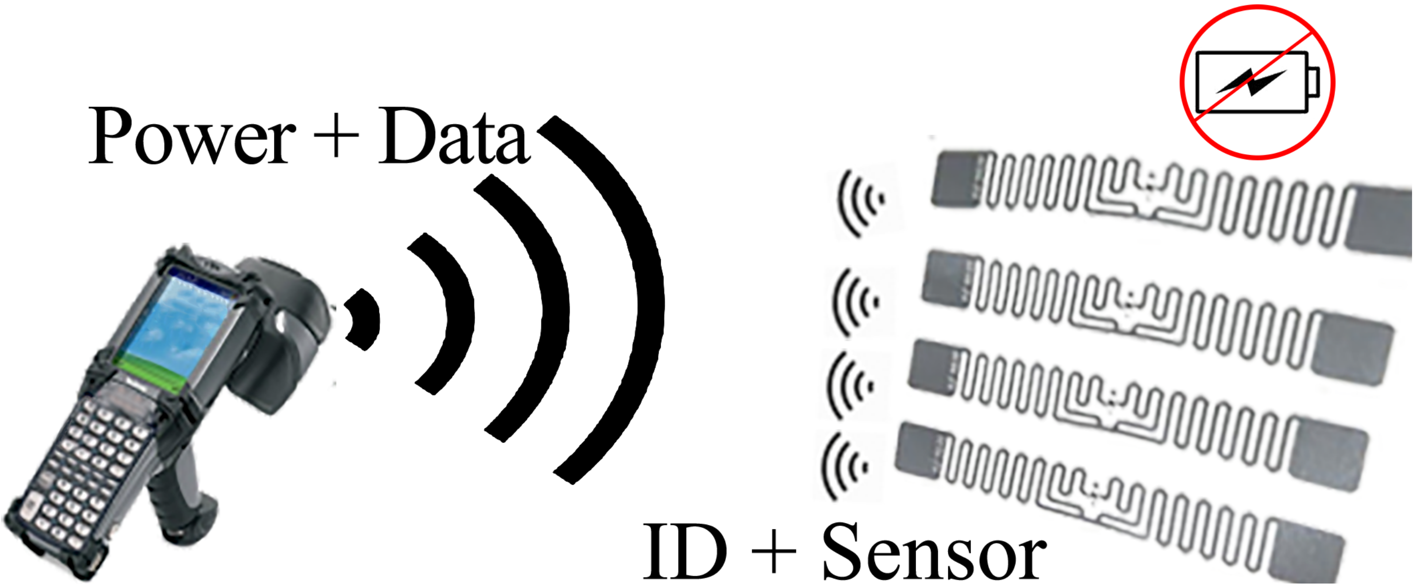
battery-less IoT radio frequency identification (RFID) sensor zero-power

1. Introduction

Wireless sensors are becoming increasingly popular in the home and industrial sectors and are used for a range of applications, from temperature or humidity monitoring to food-quality inspection of products being sold on the market. One of the main reasons for using wireless technology is that it affords non-contact, non-invasive sensing. This ability eliminates the need for long cables required for information transfer and reduces the spread of germs and brings comfort to the users. To fully exploit the capabilities of wireless sensors and automatic processes, the future generation of wireless communication, 5G, and the evolving Industry 4.0 aims to incorporate them on a massive scale. Research on wireless sensors is on a dramatic rise [1][2][3].

A sensing element may be incorporated in any of the aforementioned categories to design an RFID sensor. Using active or semi-passive technology requires a power source, which makes the wireless sensor bulky and expensive, whereas passive technology is much cheaper, but incorporating sensing elements in it is quite challenging due to the limited available power and flexibility. Hence, passive technology must be carefully engineered to address these challenges [3][4][5][6][7][8][9][10][11][12].

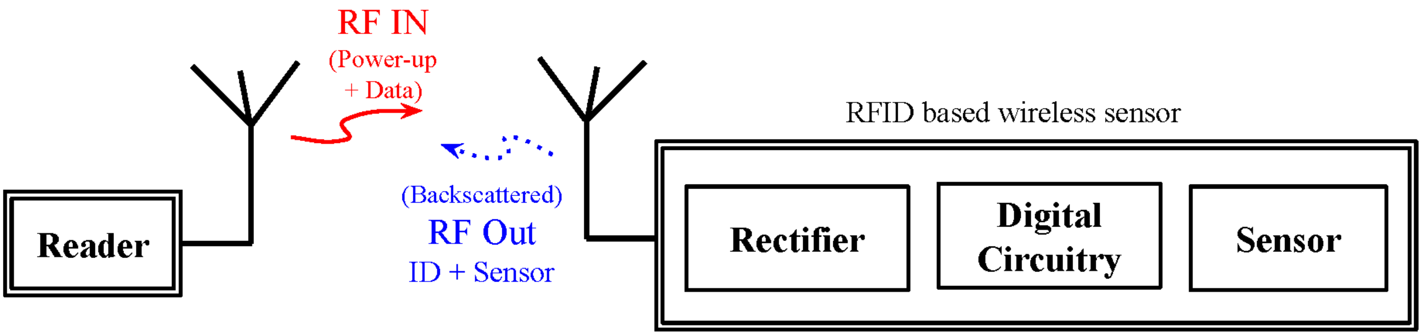
RFID is now a widely used technology for tracking and inventory management services and, as such, is governed by several design standards [13]. However, wireless sensors, especially RFID-based sensors, are still an emerging technology and might be referenced using different names in the community. Particularly, passive wireless sensors are sometimes also termed battery-less, self-powered, or even zero-power [14][4][15][16][17][18][19][20][21][22].



The remainder of this article is organized as follows. In Section 2, we discuss the individual components of RFID-based wireless sensors to develop a basic understanding of how they may be engineered to meet the requirements, e.g., complexity, cost, size, read range, and accuracy of a given application. In Section 3, the system topologies of different categories of battery-less RFID-based wireless sensors are discussed in the context of their complexity, cost, size, read range, and accuracy. Finally, potential future directions are presented in Section 5, and then, the paper is concluded in Section 6.

2. Individual Components of an RFID-Based Wireless Sensor System

An RFID-based wireless sensor consists of several components. A block diagram of all the key components is shown in the figure below, and details of each component are discussed in the following paragraphs.



An antenna is a transducer that converts free space electromagnetic energy to guided electromagnetic energy and vice versa to enable wireless communication in an RFID system. Although any radiating structure can be termed as an antenna, the efficiency with which it can transform the electromagnetic energy plays a major role in determining its amenability for use in sensor communication [23].

A rectifier in an RFID tag is the main circuit that converts the incident electromagnetic energy received by the antenna into a DC supply voltage. This voltage is required to operate all the internal circuitry of the tag, which includes the analog circuitry, base-band DSP circuitry, and memory of the tag [24][25][26][27][28].

If standard threshold voltage CMOS devices are used, the rectifier cannot be turned on when the voltages at its terminals are lower than its turn-on voltage, which affects the read range of the RFID tag. Solutions using near differential-drive rectifier, photovoltaic-assisted rectifier, and zero threshold-based technologies such as Silicon-on-Sapphire and Hetero-junction Tunnel FET provide a significant improvement to the read range [29][30][31][32][33][34][35][36][37][38].

3. System Topologies

Different arrangements and utilization of the RFID tag's components can result in different topologies. There are five principal topologies used, each offering different levels of complexity, cost, read range, and accuracy.

The simplest form of RFID sensor requires no integrated circuits (ICs) and communicates sensed data by simply varying the radar cross-section (RCS) of the tag at a certain frequency. To read data from a chip-less RFID sensor, a reader transmits a frequency sweep signal of a specific bandwidth and analyzes the backscattered signals that it receives. These backscattered signals are affected by the physical location of the sensor and its RCS. If the physical location and distance between the sensor and the reader are fixed, then the effect of the physical location can be easily factored out to determine the RCS, specifically of the sensor [39][40][41][42].

To address the challenge of multi-path propagation and to support multiple sensors in close proximity, wireless sensors must incorporate digital communication techniques. This is achieved in chip-based RFID tags, where the backscattering is digitally controlled and acts as a digitally modulated signal. This topology ensures that the power-up signal reaches the RFID tag without any significant loss. The backscattered signal is sent to the sensing element where an additional phase delay is introduced. Chip-based RFID tags based on this protocol can be modified in several ways to integrate sensors inside them. These modifications generally include an antenna-resonance shifting-based sensor, a multi-port architecture to remove the sensing element from the incoming signal path, a digitally integrated sensor using digital circuitry, and an ambient energy-harvesting block to get additional power from the surroundings.

Amongst all, multi-port architecture-based wireless sensors are very promising as the sensor utilizes a hybrid of digital and analog communications. Maximum received signal power is ensured by removing the sensor from the incident signal path and information is incorporated in the phased of the backscattered digital signal. Although having a sensor circuit introduces extra loss in the backscattered signal, the reader is connected to a power source and can interpret and demodulate a fairly low-power signal. Therefore, this topology provides an improvement in terms of read range compared to other topologies. Since the sensor information is a hybrid of digital and analog communication, the required bandwidth is low. However, having a multi-port device requires components that may increase the cost by a few dollars. Sensors with medium accuracy operating at a range of 7 m have been reported in [43][44][45].

The sensor information may also be digitally integrated along with the identification however the main challenge is having digital circuitry that operates at very low voltage and uses a minimum amount of power to read the sensed value with suitable accuracy. This added circuitry can significantly reduce the read range of an RFID chip and can slightly increase its cost. Currently, sensors utilizing this topology have been demonstrated with read ranges of around 0.7–2.2 m [46][47]. It should be noted that, since the sensor information is communicated digitally, the accuracy is high and the bandwidth is the same as a regular RFID chip.

4. Future Directions

Although a vast amount of research has already been carried out on battery-less RFID-based wireless sensors, it is clear that a great deal of potential remains for future discoveries. Among the several sensor parameters discussed in this review (e.g., read range, accuracy, cost, and size), it is evident that an improvement in sensor read ranges is still of prime interest to the community. By looking at the aforementioned topologies, we can deduce that a combination of chip-based multi-port and ambient energy harvesting can yield a much higher range—theoretically, up to 50 m.

We also saw that the size and cost of the multi-port topology are not optimal but may be significantly improved through the use of highly miniaturized antennas employing novel matching techniques to enable compact, long-range RFID-based battery-less wireless sensors [48][49].

If accuracy is a concern, digitally integrated sensor topologies with ambient energy harvesting show a great deal of promise. To increase the read range, ambient PV and RF energy may be combined. Moreover, the fabrication of the rectifier circuitry must be engineered to achieve better results. This involves using detailed models of the fabrication process that produce more accurate results and higher consistencies between different batches.

Lastly, we observed that there is a scarcity of sensor components operating in the low GHz range. Research that seeks high-frequency sensing component designs is also needed. This will allow RFID-based battery-less sensors to be used in many new applications, readying them for deployment in the future Internet-of-Things.

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