Paper-Based Ultra-Low-Cost Integrated RFID Tags for Sensing and Tracking Applications

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Abstract

In this paper, a novel Radio Frequency Identification (RFID) prototype is proposed with an embedded power source and other energy harvesting mechanisms on low-cost paper based substrate. Integration of RFID electronics, such as antenna, Integrated Circuit (IC) and sensors are also discussed for a variety of applications in transportation, logistics, and security. In addition, RFID antenna designs for high "global" bandwidth operation and rugged environments are discussed. A brief description of the protocol used in RFID ISO18000-6C will conclude the paper.

I. Introduction

RFID is one of the best low-cost candidate technologies for wireless identification for several reasons. RFIDs do not depend on any line of sight to communicate with an RFID reader, can read from multiple tags simultaneously, can modify or erase information already defined in tags, such as the WRITE or KILL command. In addition, RFID's may be utilized for transmitting sensing information with the current Gen 2 protocols since this standard describes data transmission without regard to their nature (sensed data vs. user defined data) [1].

RFID also keeps finding countless applications that include Aero-ID, anti-counterfeiting, space, healthcare, pharmaceutical and sensing. Due to the interest driven by the applications mentioned; flexible, reliable (such as thermal and/or mechanical stress in harsh industrial environments) and compact RFID tags are required. In addition, a fast and secured RFID communication should be guaranteed.

Compared with the lower frequency tags (LF and HF RFID bands) suffering from limited read range (up to 1 meter), RFID tags operating in the UHF band could potentially find the widest use due to their higher read range (up to 9 meters in passive RFID configuration). UHF RFID band also has a higher data transfer rate (currently up to 640 kbps for Gen 2 RFID standard), due to the fundamental reason that in near field systems (LF and HF) the magnetic field (H) decreases as $1/(\text{distance})^3$ compared with the far field UHF where electric field (E) and correspondingly the magnetic field (H) decrease as 1/distance [2].

A proposed RFID prototype including sensing capabilities and a battery source on low cost paper substrate is shown in Fig. 1 below.

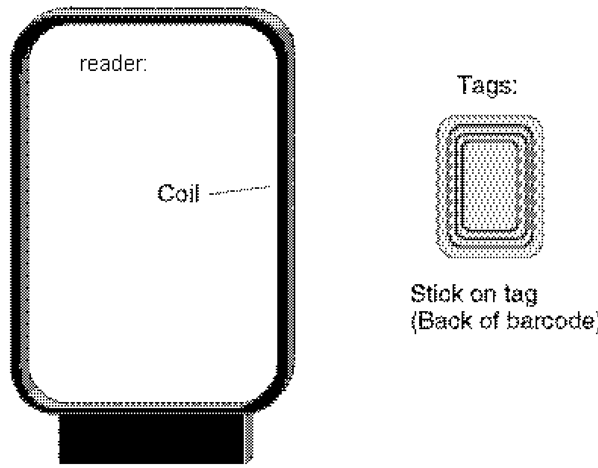

Fig 1. Loop antennas used in RFID reader and tag[3].

II. RFID Module

An RFID system comprises of a stationary transceiver, called a reader, and a mobile transceiver, commonly referred to as an RFID tag or transponder. Communication is initiated whenever a tag is brought near the vicinity of a reader. The range of the communication primarily depends on the frequency of operation. Passive RFID communication typically occurs at 135 kHz and 13.56 MHz, where at low power levels, the bulk of the energy radiated by the reader is contained in the near-field. Near-field RFID systems typically use loop antennas in the readers and the tags since they couple magnetic energy better in the near field shown in Fig. 1. However, at higher operating frequencies namely at 868/915 MHz and 2.45 GHz, communication can occur at further distances as the wavelength of the radiated fields is smaller than the required communication ranges. RFID systems operating at these higher RF frequencies, therefore, typically use patch antennas for the readers and dipoles for tags shown in Fig. 2, which can be made more directive in order to increase the range of the RFID reader system [3].

Fig. 2 also shows a proposed RFID prototype including sensing capabilities and a battery source on low cost paper substrate.

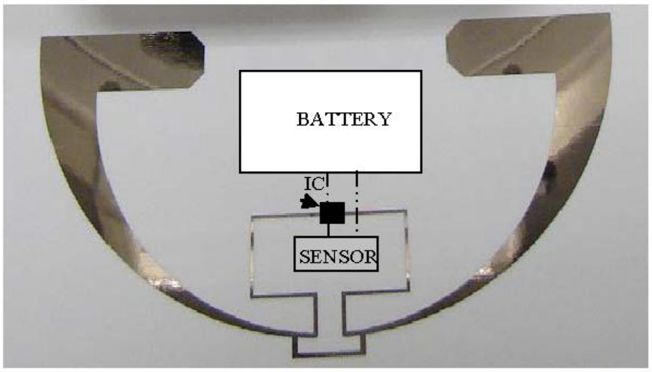

Fig. 2. Proposed prototype layout of an RFID tag with power source and sensing capabilities.

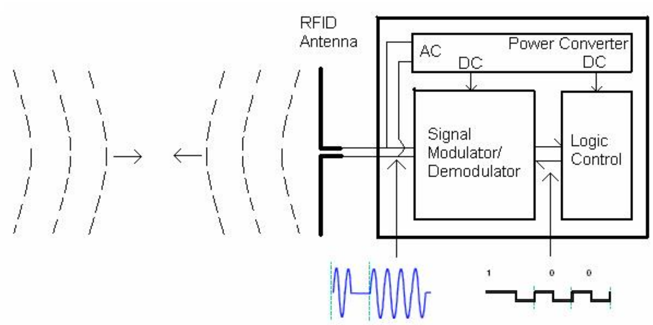

Fig 3. Block diagram of RFID tag.

Passive RFID tags use the power induced across its antenna terminals for powering themselves in addition to communication purposes. Active tags, on the other hand, use a battery to power themselves, and utilize the power induced across their antennas through EM coupling only for communication. At the heart of the passive tag to which the antenna sends and receives signals from is an IC. A block diagram of the RFID passive tag can be seen in fig 3. The IC contains a passive power converter which rectifies and filters the AC power induced across the antenna into a continuous DC mode signal, which powers the signal modulator/demodulator and the logic control within the IC. In addition, the AC voltage across the tag antenna is also demodulated into its corresponding bit scheme, which is fed into the logic controller of the IC. The logic controller decodes the instructions received from the reader, and also sends out information about the tag namely the unique identification number of the tag, also known as the GUID number, which is modulated and fed back to the tag antenna to be transmitted to the reader.

The tag uses Backscattering modulation to respond to the reader. It does this by shunting the terminals of the antenna, which changes the reflection co-efficient of the antenna to the incoming signals to its maximum [2]. This modulation produces a change in the field between the reader and the antenna which is picked up by the reader and similarly demodulated, decoded and sent to a computer connected to the RFID reader. As can be seen RFID tags allow for a very low cost and constitute an easy to implement way to communicate with the reader. Combined with the ability of readers to track multiple tags simultaneously, RFIDs provide a simple and better alternative to barcodes for retail item-level tracking.

Thus, RFIDs have found widespread use in warehousing as well as security areas. Adoption of RFID solutions by retailers, such as Walmart, in order to maintain massive amounts of inventory has brought forth the need to reduce the price per tag to a few cents, while requiring environmentally friendly materials in making the tags.

III. RFID/Sensors on Paper Substrates

Paper is considered as one of the best organic substrates for RFID applications for many reasons. It is not only environmentally friendly, but it can also undergo large reel-to reel-processing and is one of the cheapest materials known. Paper can also host nano-scale additives (i.e. fire retardant textiles) and can be hydrophobic. Most importantly, its dielectric constant ε_r is close to air's (5-6 % power reflection) allowing for the electromagnetic power to easily penetrate even after the RFID is embedded in the substrate.

Paper also has a low surface profile and with an appropriate coating paper can be made hydrophobic. This makes paper compatible with fast printing processes, such as conductive paste inkjet printing instead of metal etching techniques, which saves a tremendous amount of time in the fabrication process. In addition, this makes the RFID system much more secure since all fabrication processes can be done 'on site'. This means that the tag may be inkjet printed using conductive paste substrates on paper and with an appropriate IC integration process, such as surface-mount, assembly of a passive RFID tag can be accomplished.

Active tags, requiring the integration of sensors and batteries, can also be printed on paper in a multilayer fashion. Paper substrate can handle high temperature treatment during the assembly process in an excellent way, while its reliability/life time is very high compared to other substrates such as plastic. Paper can also be characterized easily in terms of electrical properties using resonator structures [4]. Dielectric constant and loss tangent can be effectively and accurately measured up to 40 GHz by using methods such as: microstrip ring, cavity and parallel plate resonators [4]. A suggested module of a printed RFID active tag is shown in the Fig. 2 above.

IV. RFID Antenna Design

A half wavelength antenna is typically used in RFID applications due to its omnidirectionality enabling the tags' communication with the RFID reader in any orientation and for a variety of environments [5]. The fundamental topology of an integrated UHF RFID is demonstrated in Fig. 4.

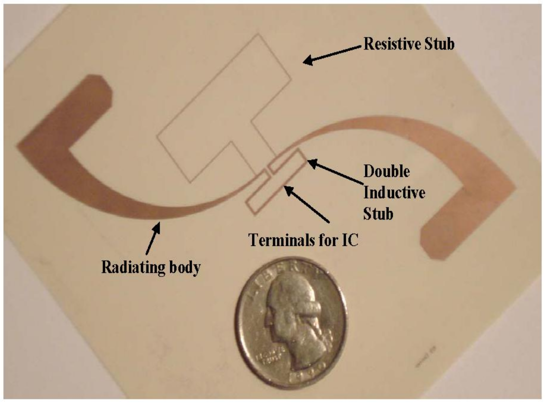

Fig. 4. Typical RFID tag architecture.

i. Bandwidth

The dimensions of the antenna shown are 7.5 cm x 7.5 cm. As shown in the figure this allows for an integrated battery and/or sensor on the top and bottom of the antenna structure. In order to match this antenna to the IC with complex impedance two matching networks were utilized. A double inductive feed and shorting stub are responsible for matching any IC impedance value hence allowing an optimum power transfer from IC to antenna [5]. The simulation and the measurement results are shown in fig. 5, demonstrating very good agreement and verifying the efficient operation of the antenna (Bandwidth defined by the VSWR of 2 or alternately Return Loss of -9.6 dB) in both European and North American bands (860 →930 MHz).

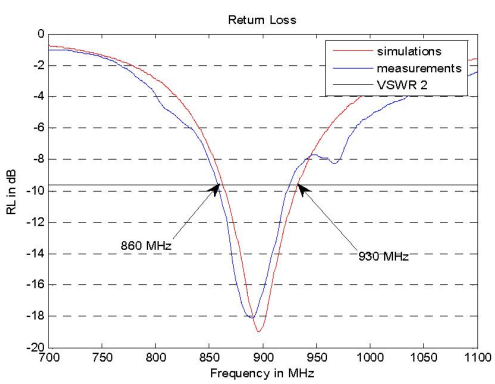

Fig. 5. Return loss of RFID tag shown in fig. 4.

ii. Harsh Environments

Antennas in UHF RFID tags, similar to the one shown in Fig.4, are linearly (vertically or horizontally) polarized. However in several industrial environments with a common presence of metals and/or liquids, the transmitted/received electromagnetic waves undergo polarization changes. This might cause a signal loss or read loss from the reader antenna due to polarization changes caused by metal and/or liquids in the vicinity. The proposed solution is a dual "polarization-diversity" antenna configuration with two identical antennas in dimensions and shape bodies shown in Fig. 6. This configuration can also account for any misalignment of the tag with respect to the reader antenna that might cause a null in its radiation pattern.

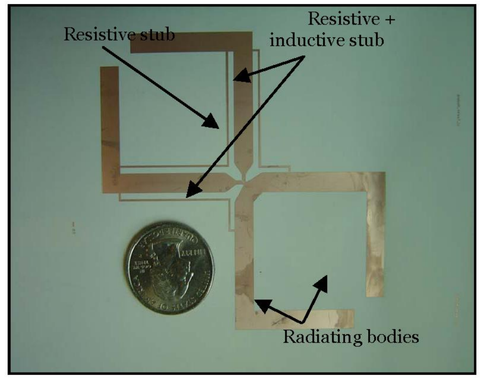

Fig. 6. Dual polarization antenna.

V. RFID Applications

A. Item-level tracking

The fundamental application of RFID is item-level tracking. Passive tag or Active tag can both serve this, depending on the desired tracking range and environmental complexity. For passive tag, the only available power is coming from the reader. The tag antenna transforms the electromagnetic wave emitted from the reader into voltage to power up the chip. The effective length is limited in this way, usually less than 30 feet. Active tags have an integrated battery as a power supply and effective length can be up to hundreds of feet, while signal quality is enhanced in rugged environments.

RFID's can dramatically increase the supply chain efficiency. Before RFID's, stockroom staff would manually record products as they arrived to the cross dock. On the sales floor, employee also had to scan many items to find out which one is running low and then go through the tedious task of finding more storage in the crowded stockroom. By using RFID's, these procedures become automatic. On every door at the back of the storage room, RFID readers will be installed. When a tagged item passes, as shown in Fig. 5, the products are automatically added to the store's inventory through its computer system. The RFID reader on the shelves also tells "real-time" the computer system about the accurate inventory level.

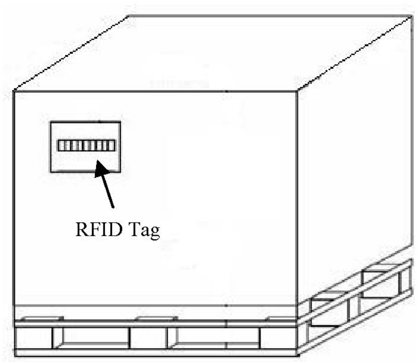

Fig. 7. Pallet with RFID label for item-level tracking.

Item-level tracking can also be used in anti-theft applications. US retailers lost more than $30 billion from inventory shrinkage in 2002, among which consumer theft accounts for 31.7% [6]. Part of this burden is passed to customers via higher prices. After RFID is implemented, it enables a retailer to know which item has been moved and when. RFID can activate real-time alarms and trigger the locking of access doors. For instance, valuable items like laptops can be tagged with RFID labels. Therefore, the reader near the shelf reads the unique ID of the RFID tag and knows the existence of the protected item. For such applications, passive RFID tags are more preferred in consideration of balancing the RFID solution cost against the benefits. When a theft happens, the reader will detect the missing of the enquired ID, and then transmits the signal to the back-end system, which initiates the other readers deployed in the warehouse to start looking for the missing tag. Whenever a reader locates the ID, a security monitor is triggered to video record the place where the item is newly detected. Almost every type of retail store can use this solution to protect its merchandise from being stolen by shoplifters.

B. Anti-counterfeiting

Besides item-level tracking, anti-counterfeiting is another major application area for RFID. The scale of lost revenue each year due to counterfeiting is billions of dollars. Prescription drugs, currency bills and luxury items are the most frequently counterfeited items, due to their generous profits. For example, the World Health Organization estimates that 5 to 8 percent of the drugs sold globally might be counterfeit, which means a possible gray market nearly $30 billion annually.

Fig. 8. A drug bottle tagged by RFID [7].

The solution is to embed RFID tags in the profit products. Every RFID tag is assigned a unique code, separating one from each other. This code will be associated with the particular prescription bottle so that it can be tracked through the supply chain. Besides that, RFID tag servers as a barcode with a "brain", in which kilobytes information can be stored. The identification information, such as drug name, expiration date, and even the description of the size/color of the container, would be stored in the RFID IC chip. After scanning, for instance, the following information would be displayed on the drug retailer's screen, "The drug is inside a 3 inch high brown bottle. Expiration date Dec.1, 2007. Only sold in Asia." If the information printed on the drug bottle has discrepancy with the one stored in the RFID, then people know counterfeiting happens. For luxury items, the idea for RFID to prevent counterfeiting is similar. Unique ID storing brand name is embedded inside the items, such as fashion clothes. When such clothes surfaces outside an authorized selling region, the RFID tag can be used to track which reseller is responsible for distributing it to the gray market. In these applications, ultra compact RFID tags are highly preferred for packaging. A demonstrated drug bottle labeled with RFID tag is shown in Fig. 8 [7].

VI. Conclusion

In this paper a low-cost paper-based RFID module has been proposed with an embedded power source, IC, and sensor. Novel antenna design methods for high bandwidth and dual polarization have been discussed. Paper as a substrate for RFID tags has been characterized and introduced for mass production of low cost substrate tags. Potential applications that might utilize this technology are also discussed in detail.

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