Battery-Powered RFID

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ABSTRACT

In this article, we compare the different types of battery-powered RFID tags that are available today and explore several emerging wireless standards that are candidates for active RFID tagging. We also present an active RFID platform we have developed and a supply chain application implemented on that platform.

INTRODUCTION

Passive (battery-less) RFID technology has been the primary candidate for tagging of cases and items, where the tags are not reused and the cost of tags is critical. However, in situations where the performance of the RFID tag is critical or a long read range is required, battery-powered RFID tags are preferred. Examples include tagging shipping containers, freight packages, valuable assets, or applications requiring sensors, such as cold-chain shipping, and asset tracking [8]. RFID tags with an onboard power source are also necessary for data-logging applications in which tags must operate independently of the reader.

The use of battery-powered RFID tags is rapidly increasing due to two important trends:

- The emergence of inexpensive CMOS Radio Frequency Integrated Circuits (RFIC) and microcontrollers now enables very low cost tags.
- The cost of batteries is dropping. More interestingly, low-cost thin-film batteries are becoming available, which enable battery-powered tags to be manufactured in the form of thin cards or adhesive labels called the Smart Active Labels [12].

In this article, we compare the different types of battery-powered RFID tags that are available today and explore several emerging wireless standards that are candidates for active RFID tagging. We also present an active RFID platform we have developed and a supply chain application implemented on that platform.

TYPES OF BATTERY-POWERED RFID TECHNOLOGIES

When considering a battery-powered RFID tag, the two basic options are active RFID tags and semi-passive RFID tags.

Battery-powered active RFID is a relatively old technology (Mario W. Cardullo claims to have received the first U.S. patent for an active RFID tag in 1973 [1]). Modern-day active RFID tags are essentially miniature radio beacons, and contain both a radio transmitter and a radio receiver circuit. Historically, the military and animal researchers have used such devices to identify and track airplanes, people, or wild animals.

Semi-passive, like passive, RFID tags do not contain any radio transmitter circuit, but simply reflect back a small fraction of the power, which is emitted by the RFID reader. Not surprisingly, this technology grew our of radar research and some of work done by the military in the 1950's and 1960's on passive antenna repeaters. In the 1970's the Department of Energy and IBM later developed a miniature version of such backscatter tags for tracking valuable assets, such as radioactive materials. In the 1980's this technology was later adopted for use in highway toll collection systems which gave rise to popular brands such as "EZ-Pass", "Sun-Pass" etc.

It is important here to consider the various technical factors that distinguish semi-passive and active RFID technologies. The major factors are listed below.

Advantages of Semi-Passive RFID over Active RFID

- **EPC compatibility** – The primary advantage of a semi-passive RFID tag over active RFID is that it can be used with existing passive RFID infrastructure. Since both passive RFID and semi-passive RFID use a backscatter mechanism to communicate with the reader, a passive RFID reader does not need to distinguish between these two types of tags. There exist long-term plans for EPC Global to develop an EPC standard for active tags as well (Class 4 or Class 5); however, this will probably not happen for some time.
- **Lower Tag Cost** – Since a semi-passive RFID tag does not require a radio transmitter circuit, the cost of the electronic tag chip can be less than that of an active RFID tag. However, single chip solutions are now available for both, and the difference in cost is small relative to the cost of the battery, for example. It should also be noted that the active RFID chips are also being used in other industries such as sensor networks and manufactured by many vendors; thus in the near future, due to the economies of scale, the cost of an active RFID chip may actually be less that the cost of a semi-passive RFID chip.

Advantages of Active RFID over Semi-Passive RFID

- **Lower reader costs** -- It is important to point out that the cost of an *active* RFID infrastructure is generally much less (10X) than the cost of a passive RFID system, because the active RFID tags have longer range and the active RFID readers do not require any high-power radio circuitry.

- **Longer reading range** – Because active RFID tags contain a radio transmitter, their signal falls as the square of the distance ($1/r^2$). However, in the case of semi-passive tags, which rely on the tiny signal reflected back from the tag, the signal drops off much more severely as the fourth power of the distance ($1/r^4$). Therefore at the longer reading distance of 50 feet or so, the signal from a semi-passive tag becomes extremely weak, requiring a very sensitive reader to detect it. It should be noted that the use of the battery on a semi-passive tag helps to extend the range at which the tag will power on; however the battery does not help increase the range of the backscatter signal from the tag, which is primarily dominated by the radar cross section and geometry of the tag antenna.
- **More robust performance in real environments** – Although in the laboratory it is possible to achieve a reading range of 100 feet or more from a semi-passive tag, this is much more difficult in a real environment. Because the signal from the semi-passive tag is so small and fragile, line of sight is often required to achieve the longer reading distances. In the case of an active RFID tag, line of sight is not required, since the tag transmits its own radio signal.
- **Dense reader mode** - The case of multiple RFID readers presents a special challenge for semi-passive tags, and special care must be taken to ensure that a semi-passive tag will not be inadvertently disabled by seeing multiple readers simultaneously. Active RFID tags do not have this problem, since it is easy to implement the medium access control protocols (such as Carrier Sense Multiple Access Collision Avoidance (CSMA-CA)) as the communications between readers and tags are symmetric.
- **Lower radiated power** – Because the active RFID tags actually transmit their own radio signal, it is not necessary for the RFID reader to transmit a large amount of power (4 Watts in the US) as a semi-passive RFID reader does. In the case of an active RFID system, the RFID reader may transmit just a few milliwatts of power, which is sufficient to communicate with a tag that is over 100 feet away. Lower radiated power means less electromagnetic interference and this makes it easy to use multiple readers in dense configurations. Moreover, very low-power (and small) handheld readers can also be made for active RFID tags.
- **Longer battery life** – It is often surprising that in most applications, active tags actually have a longer battery life than a semi-passive tag. Although an active tag does require power to transmit, the amount of time that the tag transmits a radio signal is very short. Most of the time (99% or more), the tag is sleeping or taking sensor readings, and *not* transmitting at all; it is this steady state mode, which actually dominates the battery life of a tag. When the tag does transmit its information, the active tag simply sends its data packet asynchronously and then goes back to sleep; however the semi-passive tag must communicate back and forth with the reader to exchange commands synchronously, which may require the tag to be on for a longer time, even though less power is needed for this function. In addition, an active tag can be programmed to sleep or wake up upon specific events and can asynchronously transmit its information to the reader; as a result, the active tags do not need to be constantly listening for a signal from the reader, which also preserves battery life. Lastly, the modern-day active RFID tag ICs support variable transmission powers, and a tag can lower its transmit power according to the commands from the reader, which further adds to battery life.
- **Smaller tag size** – The size of a battery-powered tag is dominated by its antenna. The emerging standards for active RFID tags at 2.4 GHz enable the antenna to be less than half the size of a semi-passive tag operating at UHF frequencies.
- **Compatibility with worldwide standards** – The most recent active RFID standards (IEEE 802.15.4) have adopted primarily 2.4 GHz as their operating frequency. This frequency is available worldwide. In contrast, semi-passive tags operate at UHF frequency bands whose applicability varies from country to country.

CHOICE OF TECHNOLOGIES FOR ACTIVE RFID

Although the standards for semi-passive RFID tags is becoming well established through the EPC Class 1 Gen 2 protocol and emerging standards for Class 2 and Class 3, the standards for active RFID have only recently been adopted. Until recently, the majority of the active RFID protocols have been proprietary with no interoperability between manufacturers. Fortunately, this is rapidly changing with the adoption of worldwide radio communications standards in a variety of industries outside RFID, such as consumer electronics and industrial automation.

Since EPC Global has been slow to adopt a standard for active RFID, many companies have been looking to adopt other existing worldwide standards for use in active RFID. For this reason, we devote the remainder of this article to discussing the various commercial options for active RFID tags.

Due to the recent advances in CMOS fabrication technologies, it has become possible to manufacture advanced microcontrollers and RF communication ICs at very low cost. More significantly, the availability of low-cost devices has led to the development of several short-range (< 100m) wireless communication standards. In particular, the following international standards are now available for building active RFID systems:

1. **ISO 18000-7**
2. **IEEE 802.15.3 (or UWB)**
3. **IEEE 802.11 (or WLAN or Wi-Fi)**
4. **IEEE 802.15.4 (or WPAN, related to Zigbee)**

One might notice that Bluetooth, arguably the most popular short-range wireless networking technology, is not included in this list. We didn't include Bluetooth because we believe its network structure may not be suitable for building active RFID systems. If we follow the standard Bluetooth specification [3], communicating devices are organized in master-slave networks called "Piconets". Each Piconet can have at most one master and seven slaves. For the sake of argument, we can consider the following two possible cases for a Bluetooth active RFID architecture:

1. Reader is the master – this would mean only maximum of seven slaves (tags) could communicate with a reader at any time. Although parked-slave mode would allow more than seven tags, this mode would induce unwarranted complexity and latency in the system.
2. Tag is the master – depending on the application, there would be undesirably large number of masters (tags) talking to a small number of slaves (readers). Many masters in close proximity could lead to severe network collisions and poor network performance.

Since neither of these architectures is attractive, we don't consider Bluetooth as a viable technology for active RFID.

In the following sections, we present the relative merits and demerits of the above-mentioned four leading standards[1].

ISO 18000-7

The ISO 18000-7 standard [4] is based on the Savi active RFID protocol, which was the first commercial active RFID system employed by the US military in the early 1990's. The 18000-7 standard operates primarily in the 433 MHz frequency band.

Advantages

- This standard was specifically designed for RFID systems.
- Since the operating frequency is 433 MHz, this technology has no problems in co-existing with any of the popular wireless technologies such as Bluetooth, WLAN, cordless phones and microwave ovens.
- Based on international frequency regulations, 433 MHz offers the broadest acceptance for Active RFID [8].
- Good propagation characteristics in crowded environments as signals can move around obstructions by means of diffraction.
- Long communication range – approximately 100 m [9].
- Low power operation – approximately 20 mW [9].

Disadvantages

- Compliance with this standard involves the use of four related patents. The licensing terms are not readily available.
- No specific support for dense reader mode (multiple readers operating in close vicinity).
- No built-in support for reader-to-reader communications.
- Susceptible to interference since narrowband signals are used.
- No built-in support for security mechanisms such as encryption or authentication.
- Relatively low data rate – approximately 28 Kbps.

IEEE 802.11

IEEE 802.11 [5] is a set of Wireless Local Area Network (WLAN) standards developed by the IEEE LAN/MAN Standards Committee.

Advantages

- The cost of chipsets is falling since there is intense competition among vendors due to the popularity of this technology.
- Since the standards committee is active, the technology is continuously improved.
- Existing routers and access points can be easily modified to act as RFID readers.
- Provides robust security mechanisms.
- Highly resilient to noise and interference since the technology employs spread spectrum signals.
- Long communication range – approximately 100 m.

Disadvantages

- High power consumption – approximately 300 mW for 802.11 b [10]. This is an important issue for battery-powered tags.
- Can interfere with the existing 802.11 networks. This can be a major issue if the number of tags is large. It will be an issue even if the amount of information transmitted by tags is small because even a small packet (unit of transmission) can affect large WLAN packets.
- Designed as wireless Ethernet technology and is meant for high data rate applications.
- Operating frequency is crowded with many other wireless technologies such as Bluetooth, microwave oven, 2.4 GHz cordless phones, etc.

IEEE 802.15.3

Most commonly known as Ultra-Wide Band, IEEE 802.15.3 [6] is a set of high-data-rate Wireless Personal Area Network (WPAN) standards proposed by the IEEE LAN/MAN Standards Committee.

Advantages

- Good resistance to interference due to the nature (narrow pulses spread over a wide spectrum) of signals.

[1] It is important to understand that power consumption and communication range values can vary based on design and operating conditions. The presented values are only rough indications.

- Positions of tags can be precisely measured using the time of arrival of signals.
- Relatively low power operation – approximately 150 mW [10] when transmitting. This feature makes it highly suitable for battery-powered tags.

Disadvantages

- The standard has not been ratified yet[2].
- Very new technology. UWB RFICs are not yet available.
- Not accepted by frequency regulations in most parts of the world.
- Designed primarily to support extremely high-data-rate WIMEDIA applications.
- Relatively short communication range – approximately 30 m.

IEEE 802.15.4

The IEEE 802.15.4 [7] standard is a low-power low data-rate protocol that forms the bottom two layers (MAC and Physical) of Zigbee protocol stack.

Advantages

- Very low power consumption – approximately 15 mW. Makes it ideal for battery-powered tags.
- Defined in three different frequency bands – 868 MHz, 902 MHz and 2400 MHz. It can be deployed in most parts of the world.
- Appropriate data rate – 250 Kbps. Designed specifically for low data-rate embedded networks.
- Ratified and active standard.
- Built-in support for security mechanisms.
- Support for reader-to-reader communications can be easily added using Zigbee.
- Highly resilient to interference and noise since it employs spread spectrum signals.

Disadvantages

- Operating frequency bands are crowded with many wireless technologies such as Bluetooth, microwave oven, WLAN, cordless phones, etc.
- Tag positioning cannot be precise since the computation is based on received signal strength.

Based on this comparative analysis, we found that IEEE 802.15.4 could be the most suitable platform for building an active RFID platform for a wide variety of applications since it provides an appropriate data rate (250 Kbps) and communication range (> 50 m) at right cost (~ $3 per RFIC) and power consumption (~ 15 mW).

We have developed an active RFID system with the following components:

[2] In fact, IEEE 802.15.3 group has been dissolved since differences between members of the committee couldn't be resolved [11].

- **ZT-100** - active tag designed for large pallets and containers. It can transmit approximately 400,000 messages using 2 low-cost AA alkaline batteries.
- **ZR-100** - Wi-Fi enabled active RFID reader. It uses 802.15.4 links to communicate with RFID tags and 802.11 links to communicate with the data hub.
- **ZG-100** – data hub. Accumulates data from multiple RFID reader and sends the data over the Internet to remote servers. It also includes a programmable integrated processor that can perform RFID filtering and data processing.

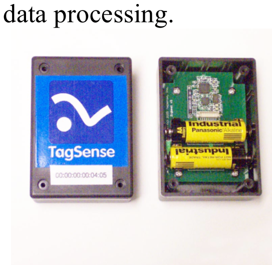

Figure 1 - ZT-100

Figure 2 - ZR100

PALLET TRACKING APPLICATION

To explore real-life usage scenarios of this active RFID platform, we developed a Pallet Locating and Tracking System (PLTS) and deployed it to analyze one segment (Printer-Wholesaler) of a magazine supply chain[3] illustrated in Figure 3. The supply chain flows as follows – first, the Publisher sends electronic files to the Printer for printing hardcopies. Next, the Printer sends the printed magazines to several Wholesalers around the country. Finally, the Wholesalers redistribute the magazine copies to local newsstands.

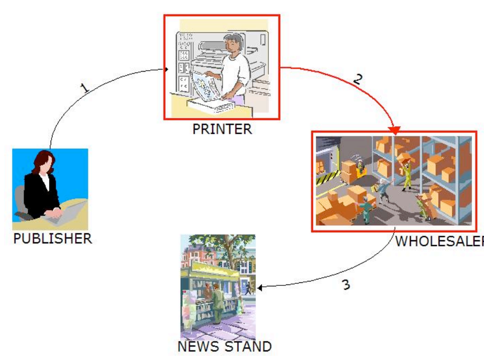

Figure 3 - Magazine Supply Chain

Active RFID systems are suitable for pallet tracking applications for the following reasons:

[3] It is important to note that PLTS can be used with all types of supply chain applications, not only magazine supply chains.

- Huge facilities can be covered using a few relatively inexpensive active readers.
- Many businesses require large pallets (with contents such as moist paper that absorb RF waves) to be tracked. Moreover, these pallets are usually stacked one over the other. Given these harsh operating conditions, passive tags may not work.

The PLTS system identifies supply chain inefficiencies by measuring the following parameters:

- **Pallet processing delay** – This parameter signifies the amount of time a pallet is kept waiting at the printer's loading docks after that pallet has been prepared. It can be computed as follows: *actual pallet dispatch time – pallet creation time.*
- **Pallet dispatch delay** – This parameter signifies the shipping delay caused by the printer and/or the delay induced by trucking companies in picking up the pallets from printer. It can be computed as follows: *actual pallet dispatch time – estimated dispatch time*.
- **Pallet transportation delay** – This parameter signifies the delay caused by the trucking companies due to road conditions and/or sub-optimal delivery schedules. It can be computed as follows: *(actual arrival time – actual dispatch time) – (estimated arrival time – estimated dispatch time)*.

The terms used in the above equations are defined as follows:

- *Pallet creation time* – the time at which a pallet is shrink-wrapped and made ready for shipping at the printer site.
- Estimated pallet dispatch time – the time at which a pallet is expected to leave the printer site.
- *Actual pallet dispatch time* - the time at which a pallet actually leaves the printer site.
- *Estimated pallet arrival time* – the time at which a pallet is expected to reach the wholesaler site.
- *Actual pallet arrival time* – the time at which a pallet actually reaches the wholesaler site.

These parameters can be observed and presented using three subsystems that form PLTS – Printer (Manufacturer) site system, Wholesaler (Distributor) site system and the Central Server. These subsystems are described below.

For this illustration, it is assumed that estimated pallet dispatch and arrival times can be computed from historical data. On the other hand, the creation, actual dispatch and arrival times must be determined for every pallet, and are measured using active RFID devices.

PRINTER SITE INSTALLATION

The printer site, where the pallets are assembled, as shown in Figure 4, contains the following three components:

1. Tag programming station - the programming station is a PC with a touch screen and a special RFID reader. It is used to associate tags and pallets in the system. The tag ID (read by the reader) and the pallet number (must be entered using the touch screen) are transmitted to a central server to create the association between that tag and the pallet. Once a tag and a pallet are associated, the pallet can be tracked by reading the associated tag. The time at which a tag is associated with a pallet is considered as the *Pallet Creation Time*.

The process of associating a tag and a pallet is called "programming" the tag. Programmed tags must be attached to the corresponding pallets.

2. Loading dock readers - The tagged pallets are kept in the loading docks and the readers in the docks read them until the pallets are loaded onto trucks. The latest time at which all readers stop reading a specific tag is considered to be the *Actual Dispatch Time* of the associated pallet**.**

When the trucks are ready, the pallets are loaded onto trucks to be transported to different wholesaler sites.

3. Hub - The hub aggregates data from multiple readers and propagates it to the central server over Internet.

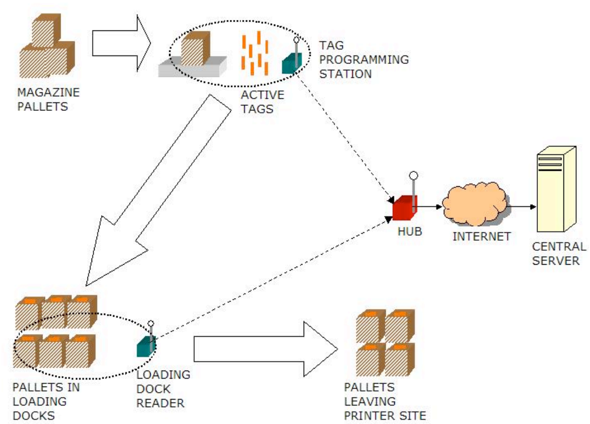

Figure 4 – Printer site subsystem

WHOLESALER SITE INSTALLATION

As shown in Figure 5, the wholesaler site, where the pallets are received for redistributing their contents to newsstands, contains the following two components:

1. **Receiving area readers** - Tagged pallets arrive at the receiving area of wholesaler's facilities. The RFID readers in these areas can read tagged pallets when they arrive. The earliest time at which any reader (at the wholesaler site) reads a tag is considered to be the *Actual Arrival Time* of the associated pallet.

2. **Hub** - Similar to the hub in distributor sites, the hub at wholesalers aggregates data from readers and propagates it to the central server.

SYSTEM PERFORMANCE

This PLATS system has been running for the past 5 months at 3 sites. The system has performed well – 99.5% read rate and excellent battery life. For instance, if a tag is sending acknowledged beacon messages every 30 seconds, a tag can be used without battery changes for 594 trips (a trip is defined as one shipment transportation from a printer to a wholesaler), if a trip is 5.5 hours in duration; a tag can make 272 trips, if trip is 12 hours in duration. Obviously, the battery life is dependent on the duration of trips, message rate, size of messages and whether the messages require acknowledgements.

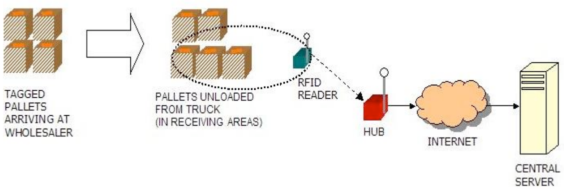

Figure 5 – Wholesaler site subsystem

The deployed PLTS system has collected extensive data[4] about the operation and performance of the magazine supply chain. This data has been useful in identifying performance bottlenecks in the supply chain. For instance, we could collect the following useful information:

- Location of pallets - the facility at which each pallet is currently stored and the number of pallets at each facility.
- Processing delay statistics – delays induced at the distributor site and at the wholesaler site, transportation delays, average delays, seasonal variations etc.
- Processing delay predictions – based on the above statistics, we could predict the delay that could be caused by weather conditions, by transportation companies, competing products and so forth.

CENTRAL SERVER

The central server contains the following two components:

1. **Application server** – it performs data collection and analysis.

2. **Web server** – it presents a web interface to pallet tracking and location information. In addition it presents sophisticated statistical data and tools.

CONCLUSIONS

As demonstrated in the magazine supply chain application, IEEE 802.15.4 based RFID platform could be efficient, economical and reliable. We also find that this platform could be used for a wide variety of applications. For example, we are currently exploring the possibilities of designing a prisoner tracking and a construction supply chain management using our IEEE 802.15.4 based active RFID platform.

[4] Due to the confidential nature of data, it cannot be published.

We find that IEEE 802.15.4 to be especially suitable for active RFID systems because of the following features of IEEE 802.15.4:

- Bi-directional communication between readers and tags
- Potential for tag-to-tag communications
- Eight transmission power levels from 0 dbm to –25 dbm
- Built-in security suite
- Tag controlled anti-collision scheme
- Zigbee ready for interconnecting readers into mesh networks
- Dense reader mode can be easily implemented using CSMA
- Appropriate data rate (250 Kbps)
- Low cost devices
- Low power consumption
- Long communication range

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