Radio Frequency Identification (RFID) has become and will continue to be very important in the area of automatic identification. The purpose of this article is to discuss the various circuit designs of two RFID components — the antenna and the reader — performed by various individuals and organizations. The reader circuit design is more complex than for the antenna. It is found that limited information, for both antenna and reader circuit designs, has been published since most of it is proprietary. Therefore, this article provides various crucial design concepts of antenna and reader.

Radio Frequency Identification (RFID) has become and will continue to be very important in the area of automatic identification. Regarded as a potential successor to the bar-coding technologies and other automatic identification methods that are used today, RFID’s significant advantage is the contact-less, non-line-of-sight nature of the technology. RFID has the ability to allow energy to penetrate goods and read a tag that is not visible. Tags can withstand harsh, rugged environments and can be read through a variety of visually challenging substances at remarkable speeds. The ability to receive, modify and pass on information, as well as being able to store data in large memories regarding any object embedded with a tag, brings a whole new dimension to its various applications.

A basic RFID system consists of three components: antennas, a reader and a tag. The antennas are attached to the reader and the tag and are the liaison between the two, which control the system’s data acquisition and communication. A reader typically contains a radio frequency module (transmitter and receiver), a control unit and an additional interface (RS232, RS485, etc.) to enable it to forward the data received to another system.

**CATEGORIES OF RFID SYSTEMS**

Today, various types of RFID systems are used, depending on their applications needs. RFID systems can generally be divided into two major types, in terms of wireless communications between the reader and the tag, and in terms of its carrier frequency.

**Wireless Communications Between the Reader and the Tag**

Two wireless communication methods distinguish and categorize RFID systems: inductive coupling and propagating electromagnetic waves. The former applies to RFID systems.

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| TABLE I  
**RFID FREQUENCIES FOR PASSIVE DEVICES**  

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>LF 125 kHz</th>
<th>HF 13.56 MHz</th>
<th>UHF 868-915 MHz</th>
<th>Microwave 2.45 GHz and 5.8 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical max read range (passive tags)</td>
<td>&lt; 0.5 m</td>
<td>~1 m</td>
<td>4–5 m (for unlicensed readers) 10 m (for site license in the US) 33 cm (in Europe due to current power restrictions. However, this is expected to improve to near 2 m as power emissions increase from 0.5 to 2 W.</td>
<td>~1 m</td>
</tr>
<tr>
<td>General characteristics</td>
<td>Larger antennas resulting in higher cost tags. Least susceptible to performance degradations from metals and liquids.</td>
<td>Less expensive than LF tags. Best suited for application that does not require long reading range of multiple tags. Has the widest application scope.</td>
<td>In large volumes, UHF tags have the potential for being cheaper than LF and HF tags due to recent advances in IC design. Offers good balance between range and performance – especially for reading multiple tags. More affected than LF and HF by performance degradations from metals and liquids.</td>
<td>Similar characteristics to the UHF tag but with faster read rates. Drawbacks is microwaves are much more susceptible to performance degradations from metal and liquids. Offers the most directional signal, ideal for certain applications.</td>
</tr>
<tr>
<td>Tag power source</td>
<td>Mainly passive using inductive coupling (near field).</td>
<td>Mainly passive using inductive coupling (near field).</td>
<td>Active and passive tags using E-Field backscatter in the far field.</td>
<td>Active and passive tags using E-Field backscatter in the far field.</td>
</tr>
<tr>
<td>Typical applications today</td>
<td>Access control, animal tagging, vehicle immobilizers.</td>
<td>Smart cards, access control, payment, ID, item level tagging, baggage control, biometrics, libraries, laundries, transport, apparel.</td>
<td>Supply chain pallet and box tagging, baggage handling, electronic toll collection.</td>
<td>Electronic toll collection, real time location of goods.</td>
</tr>
</tbody>
</table>

using low frequency (LF) and high frequency (HF) bands, whereby two resonant circuits are tuned at frequencies as close as possible. The latter applies to RFID systems operating in the ultra high frequency (UHF) and microwave band. To transfer data efficiently via the air interface requires the data to be superimposed (modulated) upon a carrier wave. Modulations are essentially based upon changing one parameter of the transmitting field; its amplitude, frequency or phase in accordance with the data carrying bit stream.

Passive tags mostly use the principle of load modulation by changing the load of the tag's antenna (amplitude and/or phase) to transmit data back to the reader. The data can also be modulated onto a sub-carrier. Higher frequency sub-carriers are generally used for higher data rates. Other RFID systems, in the low frequency range, use the energy to charge a small capacitor and use the tuned tag circuit with an oscillator function to send a frequency shift keying (FSK) modulated tag signal back to the reader, for example. UHF and microwave systems use a backscatter modulation to communicate the data from the tag to the reader.

**Carrier Frequencies**

There are four frequency ranges generally distinguished for RFID systems: low frequency, high frequency, ultra high frequency and microwave. Table 1 shows the four frequency ranges used in the passive RFID devices with their performance overview, along with typical system characteristics and examples of major areas of application. Based on the table, the different characteristics, standards specifications, applications and performance of the LF, HF, UHF and microwave passive tags can be compared.

LF tags are notably the largest installed base due to their long existence and technology maturity. Their almost interference-free from metals and liquids characteristics gives this type of tag an added edge to track goods. However, due to their large antennas and consequently larger tags, many manufacturers are turning to higher frequency ranges to save cost. The low reading range and LF data rate are two other drawbacks. On the other hand, HF tags are gaining popularity worldwide due to the adoption of smart cards in many current applications, such as personal identification, personnel access control and in transportation. Cheaper tags, longer reading ranges and faster read rates of UHF and microwave tags are the major factors that make these frequency range tags attractive to the RFID scene. Unfortunately, the usage is deterred by restrictions of the allowed power. The power allocation is different in the US and Europe. For example, in the US, 4 W of effective isotropic radiated power (EIRP) is allowed for the 915 MHz tags, whereas in Europe, about 0.5 W of equivalent radiated power (ERP) is allowed for the 868 MHz tags. Mi-
microwave tags at 5.8 GHz are not explored for use in RFID applications. It may be because of their sensitivity and inability to be read in wet places and near metals. Figure 1 shows a summary of the performance that can be expected from the LF, HF, UHF and microwave systems.

ANTENNA CIRCUIT DESIGN

The antennas are components attached to the reader and the tag and are responsible for the wireless communication between the two. Some of the antenna architectures developed to date by several researchers and implemented into RFID systems are described. Some have already been used in current RFID systems, while others have the potential to be part of future RFID systems.

Fig. 1 Performance overview.

Fig. 2 Antenna circuit model. (Ref. 3, © 1996 IEEE)

A cavity-backed, Gunn-diode-driven, self-mixing active, inverted stripline circular patch antenna has been reported. In this design, a Gunn diode, self-mixing oscillator with a simple biasing scheme was integrated with an inverted stripline antenna to form an active antenna configuration, allowing the addition of a varactor diode in the resonator cavity to provide electronic frequency tuning. To eliminate unexpected surface modes and reduce coupling, a trapped inverted microstrip is used. The active antenna consists of an inverted stripline circular patch antenna press-fitted onto a cylindrical cavity. Figure 2 shows a simple equivalent circuit used to model the active antenna. The antenna has second harmonic self-mixing capabilities, which allows the active antenna to be used in identification systems that return a modulated second harmonic signal, simplifying the tag design since a microwave source is not needed. The antenna provides good radiation performance with cross-polarization levels 18 dB below co-polarization at boresight and operates well in a self-mixing mode with a conversion gain of 2 dB when the incoming RF signal is mixed with the fundamental frequency and a 3.7 dB conversion loss when the incoming RF signal is mixed with the second harmonic of the active antenna. A 13 percent electronic tuning bandwidth was achieved with a power variation of ±1.0 dB. Therefore, this tunable ac-

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The antenna is well suited for commercial and military applications as a transceiver for microwave ID applications or for short communication links.

At the same time, a novel microstrip antenna using an alumina ceramic/polymide, multi-layer dielectric substrate was proposed. The multi-layer configuration, in which two different materials with very different permittivities and thicknesses are stacked together, can be used for designing an antenna with selective substrate thickness. This configuration gives the antenna the advantage of being able to select the optimum substrate thickness for the desired frequency. Both 10 and 18 GHz band antennas, which are designed and fabricated on the same substrate, achieve perfect matching and acceptable radiation characteristics.

Multi-layer substrates are extremely suitable for building active array systems, integrated with active devices and monolithic microwave/millimeter-wave integrated circuits (MMIC), as well as for constructing multi-frequency antennas. Multi-frequency operations can overcome the bandwidth limitation of microstrip antennas.

As researchers are trying to design low cost tags, small size antennas play a part in helping to decrease the overall cost. Small fractal antenna structures have been proposed for RFID applications. Fractal antennas are possible designs for effective miniature and frequency-independent or multiband antennas. Compared to a conventional half-wave dipole, this antenna, referred to as the Koch fractal dipole, has approximately a 33 percent smaller projected arm length. The antenna also radiates more energy than the ordinary dipole, with the same projected arm length. Besides that, the input impedance matching and directivity can be improved. Figure 3 shows how the directivity of a V-dipole antenna can be improved with a Koch fractal curve. New, miniaturized, self-resonant meander line antennas with improved gain have been designed for application in passive radio frequency identification. The antenna shape and size were optimized by using a genetic algorithm (GA), taking into account the conductor losses.

Meander line antennas were chosen to reduce the size of the tag in the UHF band. By folding the elements in the meander, a wire configuration with both capacitive and inductive reactance, which mutually cancels, was produced. As a result, resonances occur at much lower frequencies than in the case of a straight wire antenna of the same height, at the expense of narrow bandwidth and low gain, especially when the antenna surface needs to be contained within a square with a few centimeters per side (or less, to label small objects). The antenna generally found on most UHF tags is 160 mm long. The move to cut the antenna size in half to make it fit within an ordinary barcode label results in the antenna being able to capture three percent of the energy of the conventional size antenna. This will reduce the read range dramatically, which offsets the key advantage of a UHF tag. However, Trolley Scan successfully developed an antenna for the new EcoTag, which is half the size of the typical antennas used on other UHF tags. It measures 80 by 33 mm and is far more efficient than most UHF antennas of that size. With this antenna, the EcoTag can operate at ranges as far as 25 feet (nine meters). The EcoTag antenna can be produced using simple manufacturing processes, such as printing directly onto the packaging with a printing machine using conductive ink. This design is ideal for producing tags with antennas that use conductive inks applied with a printing press. This is possible because printed antennas are in a flat plane, rather than three-dimensional.

Printed antennas are cheaper and easier to produce than the etched, solid metal antennas, and they do not interfere with the recycling of packaging. For a 915 MHz tag, the dipole antenna has an aperture of 134 cm. When 250 µW of RF power passes through that aperture, the tag will receive enough power to operate fully and communicate all its data. Parmod ink was developed, which can print at high speeds highly conductive RFID antennas on paper and also on polyester. Parmod VLT uses an organic base that decomposes and leaves an antenna that is more than 99 percent metal. These inks make the printed antennas three to 10 times more conductive than polymer-based inks. Greater conductivity means longer reading distance capability. It further reduces the cost of the antenna because less ink is needed to create an antenna with the same performance level.

A novel design of low cost broad-band dual-polarized microstrip array antennas has been reported. It uses a slot-coupled feed for one polarization, while a microstrip line feed with slotted ground plane is used for the other polarization. The array antenna can make good use of the space on both sides of the ground plane, as the feed circuits for the two orthogonal polarizations are placed on each side of the ground plane. The prototype four-element array antenna, designed at C-band, yields a bandwidth greater than 14 percent at both ports and an isolation below −30 dB is obtained. The cross-polarization levels are below −20 dB in both E- and H-planes. The array is simple in structure, easy to fabricate and low in cost.

Antenna coils can be configured in many different ways. It mostly depends on the purpose of the application and the constraints given by the mechanical setup. For example, a car immobilizer or a handheld reader requires different configurations. At 125 kHz, a thin wire is usually used for antennas with about 40 turns or more. At 13.56 MHz, printed circuit boards or thin-film technology is often used to place one to approximately seven turns. At frequencies in the microwave range, such as 2.45 GHz, the antennas are commonly designed.
as dipoles, according to the corresponding wavelength. Patch or microstrip antennas are used in RFID systems, due to their design simplicity. These antennas can therefore be manufactured cheaply and with high levels of reproducibility using PCB etching technology. The other approaches in designing the antennas include reducing the size of the tag and enabling multi-frequency operations.

**READER CIRCUIT DESIGN**

A reader is needed to communicate with the tag and to store or update information in the computer host, after the data is acquired from the tag. In the following, some advanced designs of RFID readers performed in the last two years are highlighted.

Nokia unveiled the world’s first RFID-enabled global system for mobile communication (GSM) cell phone-reader. The Nokia mobile RFID kit includes RFID reader shells, in the form of plastic housings, which fit over a cell phone and the software to enable mobile workers to scan 13.56 MHz tags and access information remotely. The software for the reader is written in the Java programming language. This RFID reader works with the Nokia 5140, a GSM phone that is water resistant and more rugged than a typical cell phone. Users simply slide off their existing Xpress-on cover and slide on the RFID reader. The software needed to run the reader is automatically loaded into the phone and the reader becomes operational. The readers use the ISO14443A communication protocol. The read range is typically 2 to 3 cm. An engineer checking a meter on a gas pipeline or other industrial equipment can simply slide on the RFID reader shell to his phone and conveniently scan the tag attached to a meter to identify which meter is being read. The phone-reader records the time of the read, and the engineer keys-in the meter reading using the buttons on the phone. The data is then stored in the phone and can be downloaded to a PC via an infrared connection. Data can also be transferred via the GSM system.

Trolley Scan launched a compact long-distance RFID reader that offers read ranges as far as 11 meters, even when tags are attached to metal objects. This reader is housed in a molded ABS plastic case, weighing just 3.5 kg and operates on main power. It functions at the UHF frequencies of 860 to 930 MHz and uses a bi-static antenna system that can read up to 500 tags in a field at a time. As the system operates on a 10 kHz bandwidth with a “tag-talks-first” protocol, the system can operate in very close proximity, something that is not possible with the currently proposed EPC and ISO18000-6 systems. The ability of the RFID readers to work in close proximity will become an important consideration in the future, with the continuing proliferation of RFID technology. This new reader complements the existing range of fixed and portable readers and offers a very impressive range performance for passive UHF technology. The reader is also compatible with the EcoTag, Ecochip tag, and the laundry tag produced by Trolley Scan and its licensees. YRP Ubiquitous Networking Laboratory unveiled the UC-Watch. The UC-Watch is an RFID reader embedded in a wristwatch. It features a function to read data based on “ucode,” an RFID code system that the Ubiquitous ID Center had developed. Users can pick up objects that contain an RFID chip to read the information, which is then displayed on the 120x160-pixel screen on the RFID wristwatch.

The world’s smallest RFID reader, known as “io,” was developed by Innovation Research & Technology. It measures 12 x 2 mm in size. For comparison, the device is smaller than a US dime. It is a near-field RFID reader and is inexpensive. The reader is expected to cost around one-tenth the price of existing technology. The “io” reader features an on-board RISC processor with low power consumption, suited to 2.7 V battery operation. The “io” RFID module reads and writes to industry-standard RFID tags and smart labels operating at 13.56 MHz. This low cost and low power reader is compliant with ISO14443A and also with the forthcoming near field communic-
ifications (NFC) standard. SmartCode did further work in its existing UHF reader by integrating the reader with cellular data capabilities. Therefore, the new reader can be deployed wirelessly to a corporate network even when there is no local area network (LAN) connectivity. This reader can operate worldwide at 900 MHz, 1.8 and 1.9 GHz, on general packet radio service (GPRS), code-division multiple access-IX (CDMA-IX) voice and data cellular networks. GPRS operates on GSM cellular systems, which have been deployed worldwide; the data transmission rate over a GPRS network ranges from 9.6 to 155 kbps.

CDMA-IX systems, which offer a peak data rate of 153 kbps, are the basis for 3G wireless systems and are prominent primarily in the US and South Korea. By providing readers’ capabilities of connecting to enterprise applications over a cellular connection, the compliance policy guide (CPG) manufacturer can track its tagged shipments without having to use the retailers’ network facilities or build out network facilities where they are not present. The cellular-enabled readers can be used to either transmit tag data as it is collected or send data at specific intervals.

The SkyRead H2 handheld reader is a higher performance RFID scanner for use in commercial and industrial applications, compared to the Nokia reader. Operating at the same 13.56 MHz frequency, the SkyRead H2 not only supports the ISO14443 but also the ISO15693 protocols. Its reading range is much better, with up to a 14 cm reading distance. Besides that, it can identify multiple RFID tags in a field. This RFID reader comes with a built-in RS232 cable to connect easily to the host. A full suite of developer tools, device drivers and software libraries are also available for quick, easy integration and deployment. There are also readers that read multi-frequency tags. The TwoSENSE (TSR222) reader, produced by Northern Apex, provides portable data collection capabilities in a variety of industrial and commercial applications. It can be configured as a 13.56 MHz reader capable of reading tags from TagSys, Texas Instruments, Phillips and all other ISO15693 and ISO14443 tags. The TwoSENSE reader can also be configured to read HF 900 MHz and communicates with EPC-compliant 64 and 96 bit UHF 900 MHz labels from Matrics and multiple vendors of UHF EPC compliant technologies. Another unique feature of the reader is the extreme flexibility of the device to allow it to function with numerous personal digital assistant (PDA) and personal computer (PC) devices. PDA devices include ipaq, Symbol, Palm or other similar PDAs that have a serial connection COM port and available interface. Texas Instrument’s (TI) S4100 multi-function reader (MFR) module is adaptable to all ISO/I ECI4443 and ISO/IEC15693 standards-compliant 13.56 MHz RFID tags, while providing an easy migration path to support current tags not fully compliant to these standards. The MFR’s unique software architecture enables users to download firmware upgrades down to the ISO standard protocol level, when specifications are adjusted or new standards are added, without changing the hardware residing in the finished reader. This capability allows end-users to make RFID reader infrastructure investments today without worrying about reader hardware obsolescence when new applications are introduced or ISO standards are modified or developed. TI’s MFR module supports multi-applications such as payment, loyalty and many smart label applications. Furthermore, the open software platform feature, a range of application and security architectures can be designed, depending on the specific needs of the application.

Omnec’s new V720 RFID gate reader also operates at 13.56 MHz. Its advantage, compared to the other readers, is that it is capable of reading up to 128 Omnic V720 RFID tags at the same time in any orientation. The width of the RF curtain can be up to 1 m, allowing enough room for a person to pass through, thus enabling human applications. The 1 m width also allow adaptation to a variety of applications, whereas previous short read ranges made these RFID applications impractical. The V720 gate reader is read- and write-able, allowing the data to be fully dynamic, always current and changeable as needed. The 13.56 MHz frequency also allows the security of the data to be accurate and transferred quickly, thus increasing the efficiency and speed of the items or people traveling through the V720 gate reader. With good noise immunity and little interference, this reader is ideal to be used as an alternative to the conventional barcode scanning check counter at a supermarket.

CONCLUSIONS AND RECOMMENDATIONS

It has been observed that antennas printed on ordinary labels or cardboard with conductive inks could, within a few years, replace conventional solid copper RFID antennae. Printed antennae are less expensive and more flexible than the solid metal ones. The use of conductive inks will cut antenna costs by 50 percent. An RFID tag with a printed antenna costs about 15 to 30 cents today and will cost less as higher speed printing machines come on line in the years to come. Soon, it could be possible to print both the IC and the antenna of a tag with inexpensive inks. Besides that, printed antennae have other advantages over solid metal antennae. They can be attached to a microchip and turned into a tag up to 10 times faster than conventional antennae. The solid metal antennae pose environmental concerns because of the chemicals used to create them and they are not recyclable. Ultimately, ink producers seek to formulate the most conductive ink possible and a chemistry that is suitable for the widest range of substrates. Excellent flexibility and adhesion at the lowest possible cost are also key considerations. RFID antennae and printed electronics will continue to evolve over the next decade and grab a significant share of the marketplace.

Several RFID reader architectures using advanced RF designs have been discussed. It is established that the reader is the more complex part of the RFID system. Different readers can vary quite a lot in complexity, depending on what kind of tag they can read and what functions they want to perform on the data read. Moreover, the readers are usually compatible with their own manufacturers’ tags. Some are able to scan tags in the specific frequency range while there are some who can read tags at multiple frequencies. While
some readers do simple readings, some can perform more sophisticated functions like signal conditioning, parity error checking and correction. Readers also come in various packaging, depending on their application, practicality, size constraints and convenience in their use. In general, a practical reader should be robust, user friendly, able to read at any orientation and to read multi-frequency tags. The need for longer reading ranges of a reader differs for various systems. Shorter reading ranges are useful in areas where privacy of tracking goods is of most concern, to avoid unauthorized scanning at a far and wider range. RFID systems supporting the recently ratified EPCglobal Inc. Generation 2 (Gen 2) specification should be produced. The EPCglobal Gen 2 is a standards-based UHF technology platform that allows for global interoperability, read/write capabilities and migration to future EPC classes. Gen 2 resolves all of the shortcomings of the older specifications, innovating and improving on global compliance, tag throughput, re-writable ability, security, privacy and robustness in high density reader environments. This new UHF RFID standard is broadly supported by users and manufacturers within the RFID industry and will facilitate the widespread deployment of EPC RFID technology in the retail supply chain.

References

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