A Radio-Oriented Introduction to Radio Frequency Identification

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This tutorial article presents the history and development of RFID, with attention to the technical issues that affect range, power consumption and usability of this technology

The once obscure acronym RFID (Radio Frequency IDentification, the use of electromagnetic waves to identify a physical object) has recently been in the news in many contexts. In this article, we'll try to explain how that single acronym is used for a number of different, but related, technologies with distinct characteristics, and examine some of the unique analog and RF problems encountered in designing RFID systems.

A Bit of History

The first application we can discover where RFID offered compelling advantages was in IFF (Identification Friend or Foe), the necessity of figuring out whether an airplane is a good guy or a bad guy. Leaving out the moral issues, the technical problem of ascertaining the identity of a backscattered reflection arose almost as soon as radar became practical in the late 1930s. There were reports by British pilots during the opening encounters of World War II that German airplanes were rolling for no obvious reason when far from adversaries and under no apparent threat. It was later discovered that these maneuvers were being used as an early form of identification; in fact, these Luftwaffe craft were the world's first passive RFID tags (nomenclature to be explained below). A warning lamp in the cockpit lit when the plane was being illuminated by German radar; the pilot then varied the attitude of his airplane in order to modulate the backscattered signal and thus indicate his nationality to the radar operator. As radar rapidly became widely used, the need for more elaborate and informative means of identification was apparent, and transponders were quickly developed to reply to radar illumination with a modulated return signal. (In RFID parlance, these would be active tags.) By the end of World War II, the Mark III active transponder, with mechanical radio tuning and 6 response codes, was in use. The modern aircraft transponder, developed in the mid-1950s, operates at 1030/1090 MHz and provides up to 4,096 ID codes, as well as optional reporting of the airplane's altitude.

Such a technology is quite sufficient for airplane identification, but these transponders are physically large, power-hungry, expensive, and have too few ID codes available, to be used for lower-cost applications. By the mid-1960s, various approaches for identifying objects using much less expensive, but much shorter-range, technologies were under investigation. Very simple tags based on magnetostriction and mechanical resonance were developed for theft prevention; these inductively-coupled tags remain widely used today.

By the early 1970s Charles Walton had patented a number of inductively-coupled identification schemes based on resonant transponders with unique resonant frequencies. Sterzer, Klensch, and others at RCA had demonstrated license-plate tags using a simple diode-based frequency doubler operating in the 8-17 GHz range. Koelle and coworkers at Sandia National Laboratories had developed a UHF scheme employing rectification of RF for tag power, subcarrier modulated backscatter, and a flexible ID code generation capability, the basics of today's UHF tags and readers.

The road from concept to commercial reali-

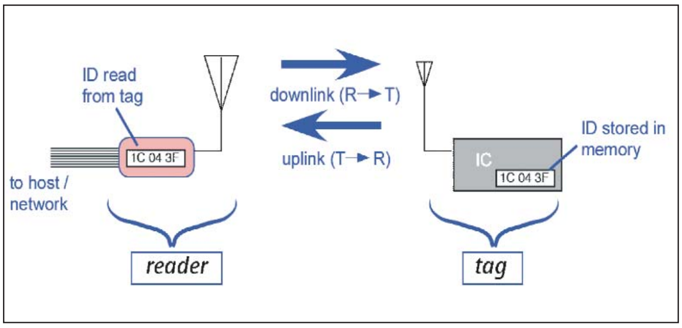

Figure 1 · Archetypal RFID system.

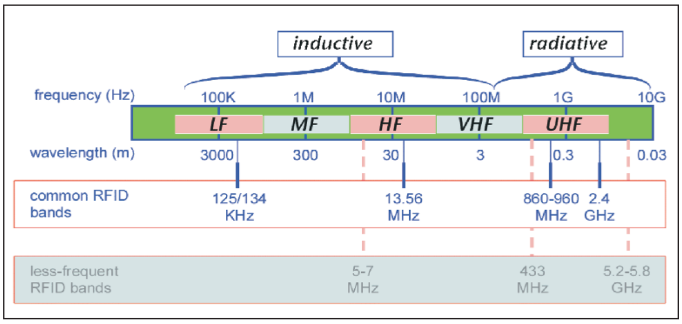

Figure 2 · Frequency bands used for RFID systems.

ty has, however, been long and often difficult, the primary obstacle being the cost of tags and readers. A 1973 article from *Electronics* magazine discusses many applications still of interest today for tagging vehicles: toll collection, toll parking, dynamic traffic control, vehicle identification, trucking location, and surveillance. Proposals for radio identification of freight containers and railroad cars appear to date from as early as 1969. Passive tags for rail cars were standardized in the late '80s, and by 1994 were essentially universal in the United States. Battery-powered UHF tags for road and bridge toll collection were introduced in the late '80s, and are now in wide use across the United States. A sophisticated traffic management system with active transponders mounted in vehicles and time-variable fees is used in Singapore to control traffic entry into the downtown area. in the 1990s, the US Department of Defense adopted sophisticated (and expensive) battery-powered active radio tags to track shipping containers after paper-based tracking systems were overwhelmed during the 1991 Gulf War.

Low-cost inductively-coupled tags are now widely used for entry control, and are becoming popular for other similar applications such as ski passes and event tickets. Specialized applications in manufacturing and asset tracking became increasingly popular in the 1990s: some examples are the tracking of airline food carts and beer kegs, or of subassemblies used in the manufacture of large systems like automobiles or golf carts.

By the late 1990s, driven primarily by the decrease in cost of silicon ICs, the cost of RFID systems had fallen to a level that enabled users to envision wider applications. The AutoID Laboratories were founded in 1999 at MIT, with cooperating laboratories in the UK, Australia and Japan, to explore the possibility of a globally-unique identification system: an Internet of Things, in which every manufactured physical object, even disposable consumer goods, could be uniquely identified and readily associated with relevant information. Sufficient progress in this direction was made by the labs and industrial sponsors to induce the formation in 2003 of EPCGlobal Incorporated, a joint venture of the administrators of the UPC (bar-code) system and EAN International. In late 2003, roughly coincident with this reorganization from development to standardization and proliferation, the world's largest retailer, WalMart, delivered a mandate to its top-100 suppliers, requiring them to provide EPCGlobal-compliant RFID tags on all pallets and the cases or cartons contained thereon by January 2005.

It was this mandate, later requirements from other large retailers, such as Tesco, Metro, and Target, as well as related requirements from the Department of Defense and initiatives by the US Food and Drug Administration, that catapulted the formerly anonymous RFID technology into the awareness of the communications industry and, to a lesser extent, the general public. Today there is considerable interest in RFID, but rather less understanding of its capabilities and limitations. In the remainder of this article we shall undertake to clarify the types of RFID systems and the advantages and challenges associated with each.

RFID Systems and Nomenclature

Every RFID system consists of at least one interrogator, more commonly known as a reader, which uses a radio link to communicate with at least one transponder, more typically a tag, as shown in Figure 1. The tag generally contains one or more integrated circuits, and a unique identifying number stored in non-volatile memory. The reader is often (though not always) integrated into a network in order to make efficient use of the identification data it collects.

There are three key architectural parameters that determine the type of RFID system in use: the frequency (practically equivalent to the mode of coupling), the means of powering the tag, and the communications protocol employed.

The radio frequencies used in RFID systems vary widely (Figure 2). The size of the reader and tag antennas varies by much less, as these are basically set by what is convenient for human beings. In consequence, for frequencies up to a few tens of MHz, the antennas are much smaller than the corresponding wavelength, and

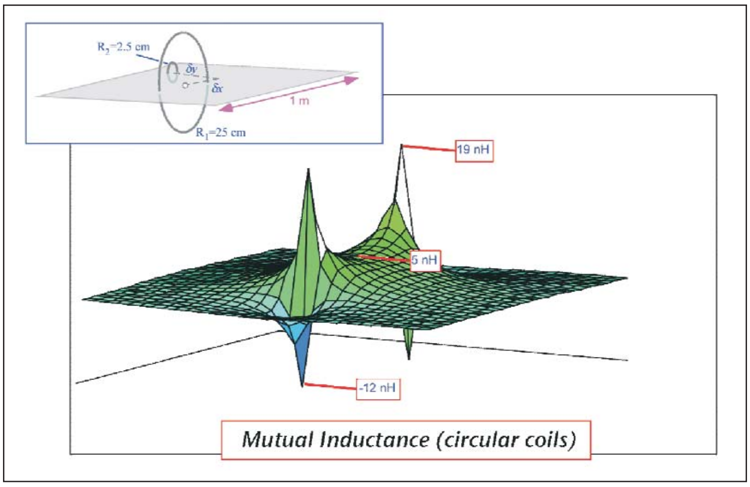

Figure 3 · Simulated mutual inductance between a 25 cm reader coil antenna and a 2.5 cm tag antenna coil.

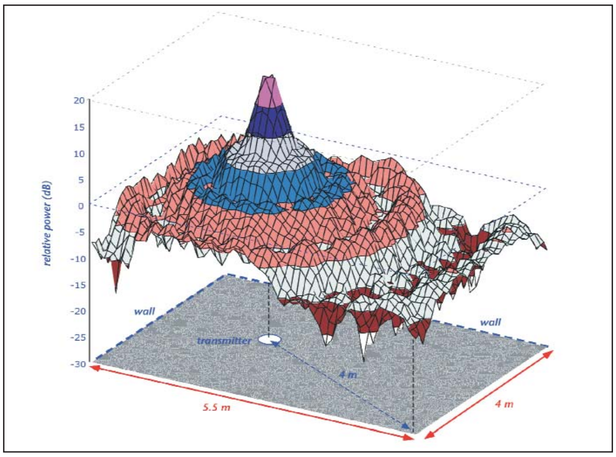

Figure 4 · Simulated received signal strength at 915 MHz; transmitter 1 meter above floor, 2 meters from walls; cubical room 10 × 14 × 3 meters.

coupling between the reader and tag is inductive in nature.

Inductive coupling is characterized by the mutual inductance of the reader and tag antennas: a current in one induces a voltage in the other. The mutual inductance is high when coil antennas are placed close to one another, but falls much more rapidly than the inverse square of distance when the separation becomes large compared to the size of the antennas (Figure 3).

As a consequence, inductive RFID systems work reliably when the reader and tag are close to one another, but read range is generally limited to a distance roughly comparable to the diameter of the reader antenna. Large reader antennas have large inductances and increased voltages, but the practical limit on antenna size is usually about 50 cm, providing read ranges of around 1 meter.

For frequencies of hundreds of MHz to several GHz, the wavelength becomes comparable to the size of typical antennas, and antennas can radiate efficiently. Power therefore falls as the inverse square of the distance, so that operation at longer ranges can be envisioned. However, the propagation environment also becomes much more complex, as reflections from building features and nearby objects interfere in an unpredictable fashion, giving rise to localized variations in RF power (fading) over lateral displacements comparable to a wavelength. A simulation of received signal strength in a simplified indoor environment is shown in Figure 4, where signal strength is seen to vary by 10 dB or more for small displacements in position when the receiver is more than a meter or so from the transmitter, with variations increasing with distance.

As a consequence, some tags may be successfully read from many meters away from the reader, while neighboring tags may receive little power from the reader. Fading can be a bigger problem than for more familiar portable radios such as cellular phones or WiFi clients because inexpensive passive tags have no power source of their own and little computational ability. Passive tags have very limited link budgets and most of the arsenal of radio weaponry—interleaving, error-correcting codes, processing gain—cannot be used.

These distinctions in the physics of coupling between the tag and reader give rise to differing characteristics and different applications for the several frequency bands. Low-frequency (LF) tags typically operate at 125/134 kHz (communications are often via frequency-shift keying between these two frequencies). The wavelength is around 2,000 meters, so these systems are always inductively coupled. Typical read ranges are around 1 meter. A photograph of a low-frequency tag is shown in Figure 5; this is a glass-encased tag that can be implanted into living animals for identification and tracking. Because the frequency is so low, coils with multiple turns and in some cases ferrite cores are used to increase the voltage induced in the tag; for example, the tag in Figure 5 has about 118 turns in the sensing coil. Such complex multi-turn coils are hard to manufacture, setting a lower limit on the cost of LF tags.

Figure 5 · A glass-encased LF tag.

The data rate of LF tags is low, because the fundamental frequency is low: 10% bandwidth at 1 bit/Hz only provides 12 kbps, and actual throughput is on the order of 1 kbps once overhead for powering the tags is accounted for. Thus, LF tags are inappropriate for applications involving very fast reads or large data sets.

The skin depth for 125-kHz radiation in solutions of conductivity around 5 mS/cm (roughly typical of tissues and dilute aqueous salt solutions) is about 2 meters: that is, these frequencies readily penetrate water and tissue. For aluminum, the skin depth is around 0.2 mm, enough to penetrate thin layers of foil or metallized packaging but not bulk metals. Low-frequency tags can be read inside animals or people, and can thus be used for animal identification. Low-frequency tags are also widely used for low-data-rate, short-range applications such as automobile ignition key fobs and payment authentication.

High-frequency (HF) tags typically use the 13.56 MHz industrial band, available in essentially all jurisdictions. The wavelength in this case is about 20 meters, so most practical antennas still operate in the inductive coupling regime; thus maximum read range is again typically around a meter for a large antenna, less for smaller coils. Data rates are no longer limited by fundamental frequency but by regulatory limitations, and tens of kbps can be achieved. Because induced voltage is proportional to frequency, a 13 MHz tag receives a much larger induced voltage than a 125 kHz tag and needs fewer turns. A typical configuration uses 4-8 turns of a coil a few cm in diameter, and can be readily fabricated using lithographic techniques. Thus the tags can be mass-produced in credit-card-sized form factors, and are widely employed for access control, ticketing, smart-cards, and asset tagging. Skin depth at this frequency is about 20 cm in conductive aqueous solutions so some body penetration is possible, though tags in contact with tissue may be detuned by capacitive effects.

Ultra-high frequency (UHF) tags are typically configured for use at 860-960 MHz, though 2.4 GHz tags are also used. At these frequencies, wavelength is about 33 cm, quite comparable to reader and tag antenna sizes, so UHF tags operate in the radiative regime and can have long ranges. For the low-cost passive tags popular in supply-

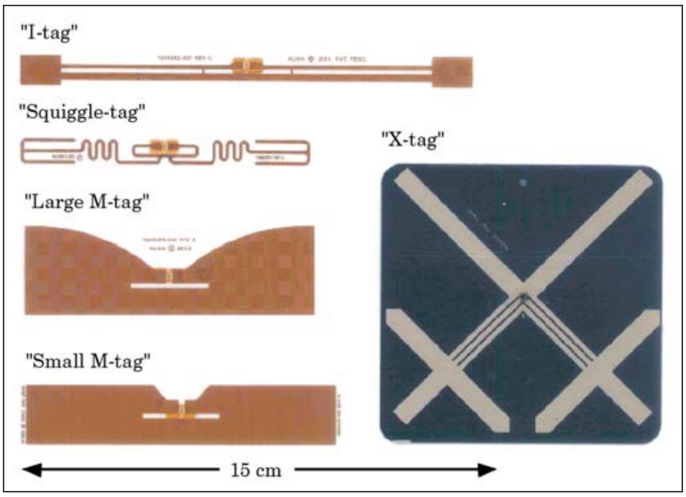

Figure 6 · Examples of commercial UHF RFID tags.

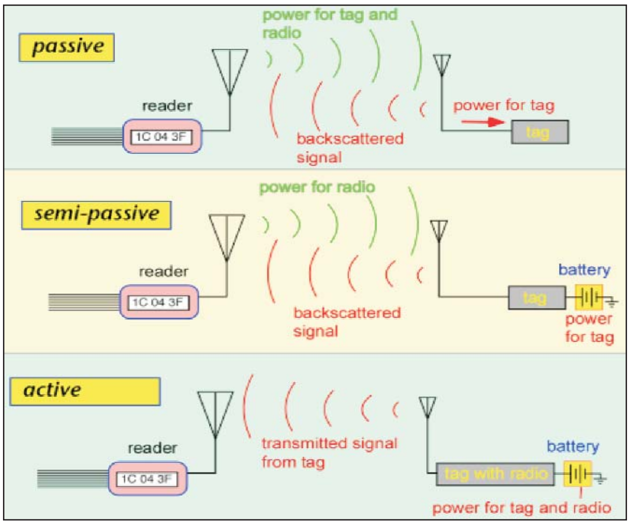

Figure 7 · UHF tag architectures.

chain applications, ranges of 3 meters are typical and 10 meters achievable. Data rates of 50-150 kbps are typical, and the new second-generation standards envision tag data rates of hundreds of kbps.

Efficient antennas are most readily constructed with dimensions on the order of a half of the wavelength, in this case around 15 cm, an inconveniently large size for many desirable applications. It is possible to compress the linear dimension by bending the conductive regions, or using large-area structures, though inevitably with some compromise in radiation resistance and thus performance. At these frequencies tags are also sensitive to environmental effects, and optimal designs may change depending on the material to which the tag is to be attached. Thus a wide variety of antenna configurations are available; some are shown in Figure 6.

Because UHF tags and readers operate in a radiatively-coupled mode, tag-reader communication is not simply dependent on distance (Figure 4); any particular tag can be in a fade and fail to respond to a reader inquiry. The tag, reader, or both, may move during read operations in an attempt to ensure that the tag will be in a high-signal-strength region during at least one interrogation. Radiative coupling and consequence long propagation range also exposes UHF readers to interference from nearby readers and other devices operating in unlicensed bands. Unlike the 13-MHz band, operation near 900 MHz competes with many licensed and unlicensed applications, including cellular telephony and mobile radio. The regulatory situation is very complex, with each jurisdiction allowing a different band or bands for RFID operation, and regulations are still in flux in many key regions.

Where does a tag receive the DC power to run the integrated circuit that contains its identification information? How does it transmit a signal back to the reader? There are three approaches to solving these problems, with differing cost-performance tradeoffs (Figure 7).

Passive tags, such as those depicted in Figure 6, have neither a battery nor a radio transmitter. Power to operate the tag IC is obtained by rectifying RF energy intercepted by the tag antenna. The IC power required is typically some tens to a few hundred microwatts, greatly in excess of the threshold for detection for a conventional radio link operating at similar data rates. (For example, a 1 Mbps WiFi radio generally has a sensitivity of around –90 dBm or 1×10^{-12} watt.) Thus the forward-link-limited range of a passive tag is a few meters to perhaps 15 meters depending on the radiated power and antenna gain. A parallel channel with shorter time constants rectifies part of the received signal to extract the amplitude-modulated information from the reader. Since there is no coherent frequency conversion and limited amplification available, tag receive sensitivity is also greatly inferior to that of a conventional radio, but the expensive and power-hungry components of a conventional receiver (synthesizer, mixer, LNA, etc.) are avoided. Finally, the tag does not transmit its own signal to the reader, but simply modulates the signal that its antenna backscatters by changing the antenna impedance. In this fashion, the tag need only provide a switching function operating at a modest rate comparable to the data rate (a few hundred kbps), rather than requiring oscillators, amplifiers, and mixers operating at 900 MHz. However, the resulting power received at the reader is dependent on the fourth rather than the second power of the distance: P_{rec} $(1/r^4)$, and falls off very rapidly, so that receive-limited range may also be only a few tens of meters.

The limited power available to the IC also limits the amount of information that can be stored and the amount of computational power available: passive tags can't be expected to deal with the array of methods used in conventional radios to ameliorate noise and fading, such as interleaving, convolutional coding, or phase-shift-keyed modulations. Finally, since there is no power available except when the tag is illuminated, it is difficult to integrate any sensing capability with the tags.

The benefit obtained from all the sacrifices in performance is a considerable reduction in cost and complexity. Commercial tags are available today at costs as low as US$0.20 in volume, with a plausible path to costs of less than US$0.10. Passive tags are small and thin, and can be embedded in adhesive labels and other unobtrusive structures, and since they have no battery they are maintenance-free and have long field lifetimes.

Figure 8 · External and internal images of semi-passive tag used for automated toll collection.

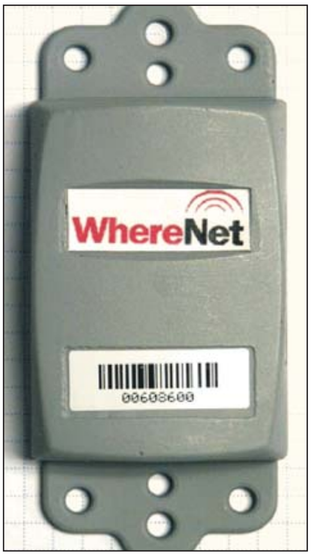

Figure 9 · 2.4 GHz active tag, providing location as well as identification information.

Semi-passive (or semi-active) tags are equipped with a battery to provide power for the integrated circuit(s), but still use backscattered communications to avoid a radio transmitter. A typical semi-passive tag used in road tolling is depicted in Figure 8. Semi-passive tags can achieve longer ranges, generally limited by reader receive sensitivity: tens to as much as 100 meters are realistic. Read reliability is greatly enhanced, since the tag no longer depends on the reader to remain powered. Semi-passive tags can be integrated with sensing capability. However, batteries must be replaced periodically, although life of up to 5 years is achieved by careful design and shut-down of most circuitry when no interrogator is present. Semi-passive tags are much larger and more expensive than passive tags, on the order of US$10-30.

Active tags are architecturally-conventional radios, using a battery to power a transmitter and receiver and well as the IC. A typical active tag is shown in Figure 9. The resulting performance improvements allow for ranges of hundreds of meters in unlicensed outdoor operation, but size and cost are very high, making active tags appropriate only for marking expensive assets or tracking people. To minimize power usage, active tags often transmit infrequent short bursts, using pseudonoise-coded schemes similar to code-division multiplexing (CDMA). These brief bursts allow for accurate time-of-arrival measurements and therefore precise location of the transmitter if multiple receivers are available; active tags are often used to provide both identity and location of valuable assets such as shipping containers in outdoor storage yards. Because they are powered, active tags can have large memory capacities and may also store shipping manifests and provide sophisticated sensing and time-stamp capability.

Summary

The major types of RFID systems have been described in this tutorial article. Future articles are planned that will expand on protocols, standards, tag and reader construction, and some RF aspects of tag usage models.

Author Information

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