From August 2005 High Frequency Electronics

A Radio-Oriented Introduction to RFID—Protocols, Tags and Applications

By Daniel M. Dobkin, Enigmatics, and
Titus Wandinger, WJ Communications

The authors' instructional presentation of RFID technology and applications continues with this examination of communication protocols and UHF tags

This article continues the discussion of radio frequency identification (RFID) that began with a tutorial overview in the June 2005 issue of this magazine. This article explores in more detail the topics of communication protocols, UHF RFID tag technology, and the RF implications of specific RFID applications.

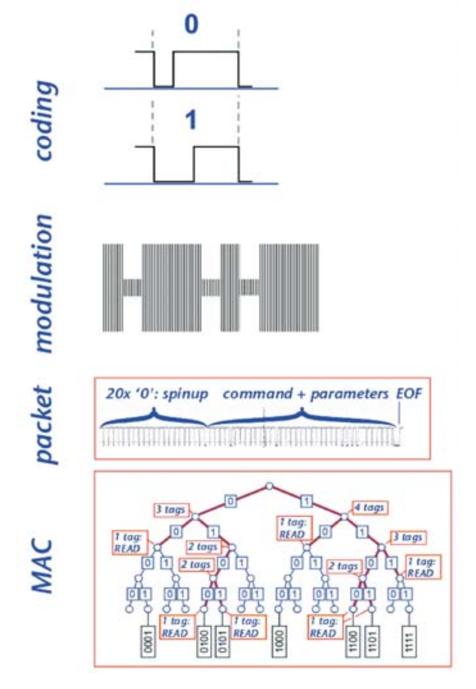

Figure 12 · Elements of an RFID communications protocol.

RFID Communucation Protocols

Every form of communication must follow a set of protocols, dealing with such issues as providing access to the communications medium, structure and meaning of the data to be transmitted, and coding and modulation of the data into the transmitted signals (Figure 12).

There are many distinct protocols used in various RFID systems; some are listed in Table 1. The protocols have been developed somewhat independently and even when standardized are generally mutually inoperable. For example, an ISO15693 tag doesn't detect or understand an ISO11784 reader, and neither can communicate with an EPCGlobal UHF system. In some cases a family of protocols may have some higher-level commonality (e.g., ISO11784-5 and 14223, ISO18000).

Because of the distinct physical layer operation, LF, HF, and UHF tags generally use different means of coding and modulation. LF systems often employ frequency-shift keying of the fundamental, for example between 125 and 134 kHz, to transmit signals to the tag. HF systems use coded amplitude modulation of the carrier, such as Miller modulation, with subcarrier modulation (periodic variation in the amplitude of the 13.56 MHz carrier) often at 847 kHz ($f/16$) for the tag-to-reader link. UHF systems also often employ coded amplitude modulation for the reader-to-tag link, along with various subcarrier schemes for tag-to-reader communications. Reader modulations are constrained by the need to simultaneously power the tags; for example, simple return-to-zero schemes, in which a '1' is encoded as a high signal and a '0' as no transmitted signal, would be vulnerable to loss of tag power during long strings of zeros. Because of the limitations of passive tags, many of these

FREQUENCY	125 kHz	5-7 MHz	13.56 MHz	303/433 MHz	860-960 MHz	2.45 GHz
TAG TYPE						
Passive	ISO11784/5, 14223 ISO18000-2	ISO10536 iPico DF/iPX	MIFARE (ISO14443) Tag-IT (ISO15693) ISO18000-3		ISO18000-6 EPC class 0 EPC class 1 EPC GEN II Intellitag tolls (Title 21) rail (AAR S918)	ISO18000-4 Intellitag μ-chip
Semi-passive					rail (AAR S918) Title 21	ISO18000-4 Alien BAP
Active				Savi (ANSI 371.2) ISO18000-7 RFCode		ISO18000-4 WhereNet (ANSI 371.1)

Table 1 · Some RFID protocols, categorized by frequency and tag type.

schemes are woefully spectrally inefficient compared to common wireless modulations like QPSK or QAM schemes, with much less than 1 bit per Hz being achieved.

Packet structures and data are also distinct and usually incompatible between protocols, though in most cases the general structure of synchronization|header|command| data is present. Many schemes provide simple error checking through a cyclic redundancy check (CRC), which is essentially a hash scheme in which the transmitted data, regarded as a binary number, is divided by a fixed constant and the remainder, typically 16 bits, is transmitted for comparison with that independently calculated by the reader or tag.

In most cases only one reader is active in any given physical location, so medium access control for RFID is focused on resolving the potential conflict between a number of tags all simultaneously present in the reader field. Most schemes are variants of two basic approaches: binary tree resolution, in which each populated branch of the tree formed from all possible unique ID numbers is traced until the tags in that branch are reached, or Aloha access schemes, in which tags talk in a random or pseudorandom sequence and back off if an attempt to communicate is unsuccessful.

As noted in the first article, in 2003 EPCGlobal was formed to establish and promulgate RFID standards for supply chain and related applications. Some of EPCGlobal's earliest activities concerned the definition of the electronic product code (EPC) itself. EPCs can be 64, 96, or in the future 128 bits or longer, though the current trend is strongly away from using 64-bit codes. The EPC is partitioned into a header, describing the structure of the remainder of the code, some optional filtering, a 'manager' number (typically a company or organization), an 'object class' (a model number or SKU), and a serial number. The addition of the serial number is what makes the EPC unique to a specific physical object. Conventions are also available for mapping several common existing identifiers into EPC's: the general trade identification number (GTIN) familiar to most of us as the bar code on consumer products, the serial shipping container code (SSCC), the global location number (GLN), the global returnable asset identifier (GRAI), and the global individual asset identifier (GIAI). EPCs use a 16-bit CRC to detect errors.

(It is worth noting that with a 16-bit error check, there are only roughly 65,000 possible CRC values. When the total number of tag reads becomes comparable in size to the total number of CRC values, it is inevitable that on occasion a noisy or spurious EPC will by chance agree with the CRC value, leading to a 'phantom tag' read: an apparently valid tag EPC that doesn't physically exist. Since a reader left on continuously can attempt several hundred read operations per second, only a few hours of operation may be required to attain large numbers of total reads, such that a few phantom tags may be expected to be encountered.)

EPCGlobal has also promulgated several detailed standards for UHF tags and readers. The class 0 and class 1 standards documents, while never fully completed or ratified, are available on the EPCGlobal web site, and substantially conforming tags and readers are available from a number of vendors. EPC Class 0 tags are to be 64-bit, factory-programmed read-only tags, though in practice 96-bit tags are common, and chip manufacturers for this standard (Matrics-Symbol and Impinj) provide means of writing to tags in the field, albeit distinct and mutually incompatible. The reader encoding, known as pulse-interval modulation, employs varying-length signal-low pulses at the beginning of each symbol to denote binary '0', binary '1', and 'null' (a rarely-used symbol for inducing state transitions in the tags), as shown in Figure 13. Class 0 systems employ a bit-by-bit communications protocol in which the tag's response to each reader bit is superimposed on the CW portion of that bit, using either a 2.2 or 3.3 MHz subcarrier (Figure 14).

Because the tag response is at a relatively high subcarrier frequency, tag emission spectra are several MHz from the reader channels. Naturally, this fact simplifies radio design and filtering, as the carrier and any converted phase noise near it can be readily rejected in the baseband chain. Class 0 receivers generally use a homodyne image-reject mixer architecture, as this provides a baseband signal insensitive to the absolute phase of the

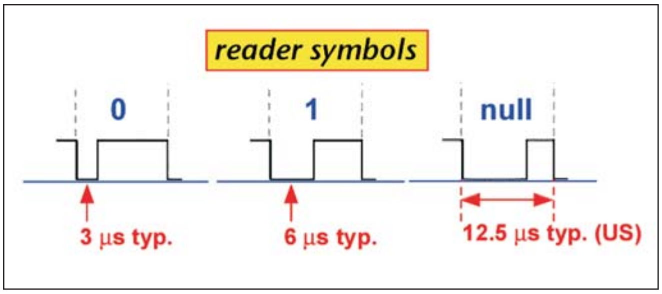

Figure 13 · Baseband depiction of EPCGlobal class 0 reader symbols.

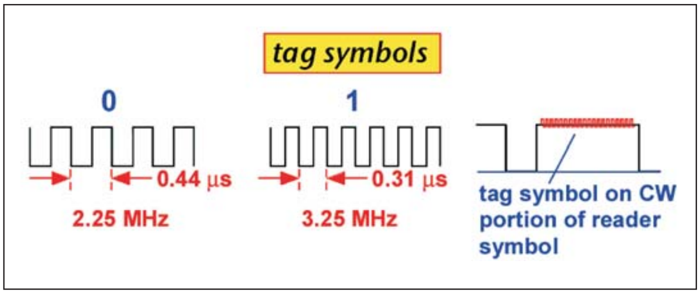

Figure 14 · Baseband depiction of EPCGlobal class 0 tag symbols and superimposition of tag reponse on reader symbol.

received carrier. However, in the case where the tag is regarded as an emitter, the distant sidebands can lead to regulatory challenges, and in environments with a number of readers, interference mitigation may become challenging.

When multiple tags are present, potential collisions are resolved using a bit-by-bit, binary-tree search (Figure 15). During a tree traversal, each tag transmits the next bit of its EPC; if the reader echoes that bit, the tag continues, otherwise it transitions to a dormant state and awaits the next traversal. In addition to the tag EPC, known as ID2 in this context, two other numbers can be used to create a binary tree for singulating tags: ID0 and ID1. ID0 is a random 16-bit number generated anew each time it is used; ID1 is a random 16-bit number permanently stored in each tag. The use of shorter IDs allows faster navigation of the tree, at the cost of some chance of a collision since these IDs are too short to be globally unique.

The class 1 standard describes tags that contain 64- or 96-bit EPCs; both types are commercially available, though use of 64-bit tags is decreasing. Class 1 tags are nominally write-once, but in practice commercially-available tags can be written numerous times and are regularly erased and reprogrammed in the field. Class 1 reader symbols are similar to those used for class 0, though there is an option to use a shorter pulse time, and the ‘null’ symbol is not used. Class 1 tag symbols use F2F coding (Figure 16) and a data rate twice as high as that of the reader-to-tag link. Note that the absolute state of the tags (‘high’ or ‘low’ reflection) cannot in general be detected by the reader; only state transitions are relevant in modulation. Because of the relatively low number of transitions per symbol, the sidebands generated by FM0 tags are typically close to the carrier. Class 1 receivers are typically implemented as homodyne I/Q chains with filtering; both I and Q branches are necessary to ensure that the tag is seen even if the reflected carrier from the tag happens to be in quadrature to the local oscillator signal. (If the reflected carrier from the tag is 90 degrees relative to the transmitted signal—also used as the local oscillator—the mixing product is (sin ωt)(cos ωt), which averages to 0.) Careful baseband filtering is needed to reject DC due to self-mixing from spurious reflections and to minimize converted phase noise.

Class 1 communications are packetized, with a full reader packet transmitted prior to any tag reply. Collision resolution in class 1 is implemented using a hybrid filter/binary-tree approach: the reader provides a subset of the EPC in its request (‘PING’) packet, and only tags whose EPC has that subset of bits respond. The responding tags choose one of 8 time bins for their response depending on the next 3 bits of their ID, and provide the next 8 bits in their response; if only 1 tag responds in a bin, the reader can request its full ID before going on to the next time slot.

Class 1 Generation II was ratified in early 2005, and prototype tags and readers are just becoming available. The standard defines a field-writeable tag with at least a 96-bit EPC. The reader symbols are pulse-interval encoded, but in this case the low portion of each symbol occurs at the end of the symbol, and is fixed in duration, while the length of the high portion is varied (Figure 17). The tag reply format is quite complex and can employ either FM0 signaling, in which a binary ‘1’ is constant during a

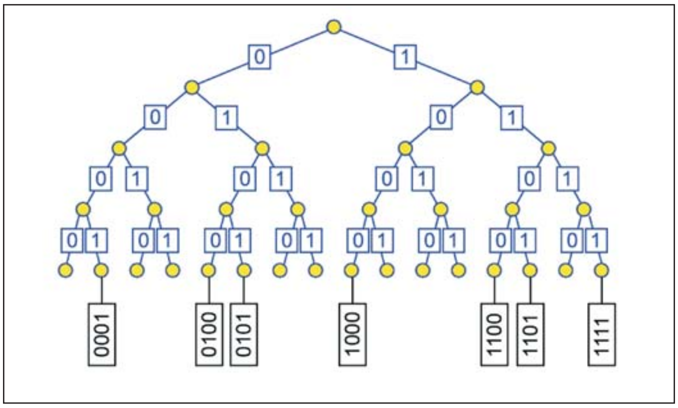

Figure 15 · Simplified binary tree partially populated with tags.

symbol time and a binary ‘0’ has a state transition in the middle of a symbol, or the FM0 symbol can in turn be XOR’d with square waves of up to 8 times higher in frequency to form a Miller-modulated subcarrier (MMS). Some of the symbols are shown in Figure 18. Note that when MMS is employed, the time between transitions is fixed irrespective of the value of M, so that higher values of M create symbols that last longer, and thus provide lower data rates but better noise immunity. The timing of the tag symbols is defined by two parameters, the link frequency and the divide ratio, both specified by the reader. The protocol provides considerable flexibility as a consequence, with data rates from around 5 kbps to as high as 640 kbps.

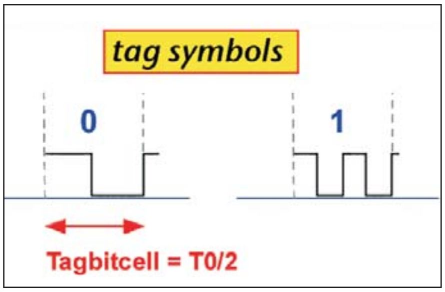

Figure 16 · Baseband depiction of EPCGlobal class 1 tag symbols (“F2F”).

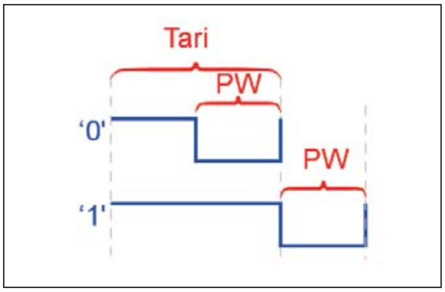

Figure 17 · Baseband depiction of EPCGlobal Class1 Gen II reader symbols.

Gen II uses a slotted-Aloha approach to collision resolution, in which tags randomly select a counter value at the beginning of an inventory operation and count down with each reader command until they reach a value of 0 and respond. The reader can adjust the number of counter values available to adapt to the number of tags appearing in the field. Each tag maintains 4 flags, allowing it to participate in four ‘simultaneous’ inventory operations. Gen II tag memory is organized in four banks, containing (respectively) KILL and ACCESS passwords, the EPC and associated data, some tag identification data, and user-defined data.

Gen II provides for some additional communications security relative to the earlier EPCGlobal standards. The EPC is never transmitted by the reader, and an encrypted mode is available for singulated tags, in which a one-time-pad is used to XOR-encode each transmitted word.

As the reader can appreciate, the class 0, class 1, and class 1 Gen II standards use incompatible signaling conventions, collision resolution, and memory mapping. (The command sets and state diagrams, not discussed above, are also unique to each type.) Fortunately, multiprotocol readers capable of communicating with either class 0 or class 1 tags are widely available, and most vendors will provide Gen II capability by the end of 2005.

UHF Readers and Tags

UHF RFID readers are available from numerous vendors, in various sizes from PC-card-compatible readers to wall-mounted readers with built-in computers and antenna multiplexing.

Because the reflected signal from a passive tag is at the same frequency as the transmitted signal (Doppler shifts are generally negligible), UHF RFID readers are homodyne radios, in which the received signal is mixed with the transmitted signal and directly converted to baseband with no intermediate-frequency (IF) stage. A generic block diagram is shown in Figure 19. The local oscillator signal is split, with one branch providing the transmitted signal, typically amplitude-modulated. Baseband filtering of the incoming data helps minimize spectral width of the output.

A circulator or directional coupler extracts the reflected signal in a single-antenna system (shown here), or separate transmit and receive antennas can also be used, simplifying the problem of TX/RX isolation at the cost of additional size and complexity. The received signal is mixed with the other branch of the local oscillator signal. Fixed reflections (from the antenna or stationary objects in the field) are converted to DC, and the tag reflected signal is converted to a baseband frequency band dependent on the data rate and subcarrier frequency used.

Several design challenges arise in constructing such a radio. Even for a well-matched antenna, or a well-isolated TX/RX pair, the transmitted signal is likely to leak into the receiver at a level much higher than that of the wanted tag reflection. For example, for a transmit power of 1 watt and antenna return loss of –20 dB (an excellent antenna), the transmitted signal leaking into the receiver is on the order of 10 dBm, versus a wanted received signal of around –60 dBm for a distant tag. This leakage causes offsets that are likely to saturate the baseband

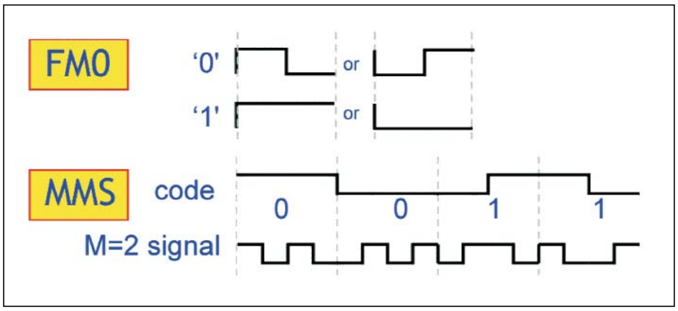

Figure 18 · Baseband depiction of EPCGlobal Class1 Gen II tag symbols. Only the M = 2 MMS option is shown here (M = 4 and M = 8 are also available).

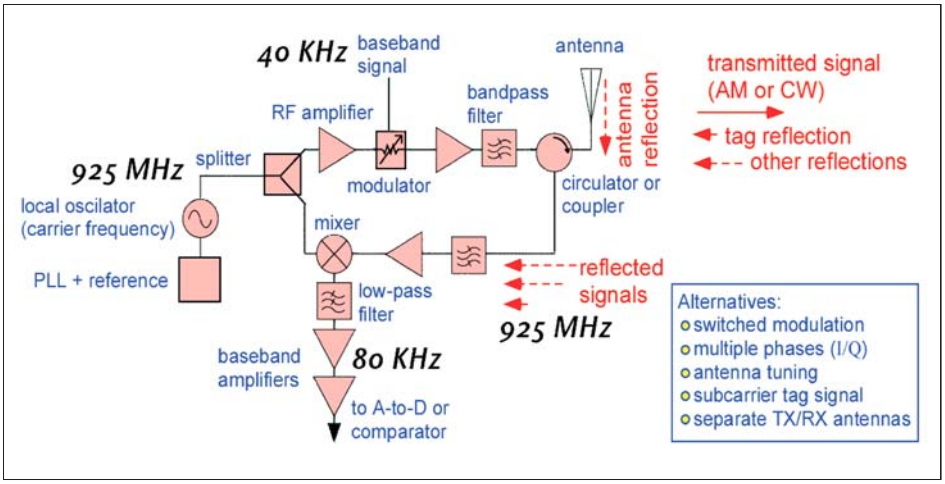

Figure 19 · Simplified block diagram of homodyne UHF RFID reader (only the "I" branch of receiver is shown).

amplifier chain if not filtered. The offsets are only at DC when the transmitted signal is constant in power (during the time the tag reply is to be received); during transmit modulation the offsets swing wildly up and down at the reader symbol rate, likely slamming baseband amplifiers into saturation. Protection circuitry and a finite recovery time after the last transmitted symbol are needed to ensure that the receiver is stable enough to allow demodulation of the initial symbols from the tag. The reflections also mix with phase noise in the local oscillator to produce noise in the baseband, which may limit read range if the reflections are large.

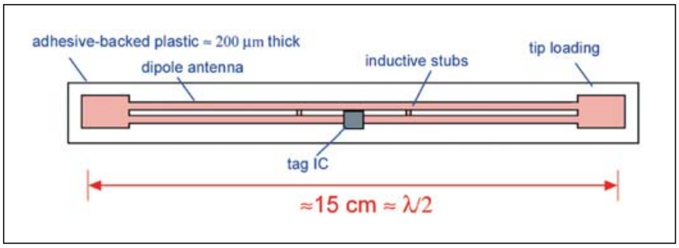

Figure 20 · Schematic depiction of typical single-dipole tag.

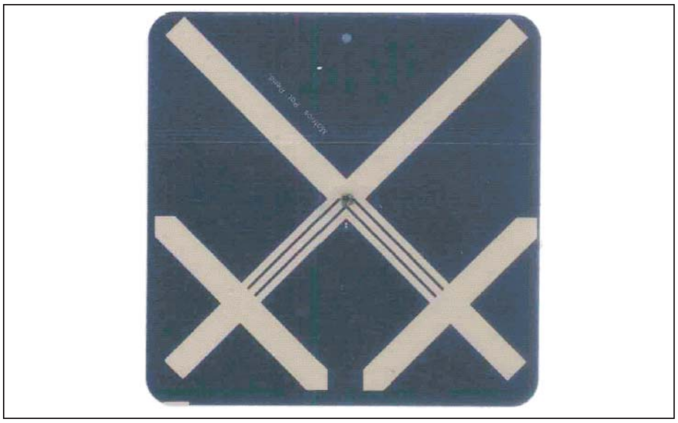

Figure 21 · A dual-dipole passive RFID tag; tag size roughly 9×9 cm.

Passive RFID tags consist of an integrated circuit mounted on a strap, the latter affixed to an inlay typically containing a conductive antenna structure on a thin plastic substrate. The inlay may be adhesive-backed and used as a standalone RF-read-only tag, or be incorporated into a conventional adhesive-backed paper label to form a human-readable RFID-enabled label.

Tag designs operate under a number of constraints, including size, cost, and compatibility with the various objects to which the tag may be attached. Antenna designs often contain elaborate features, but many fall into one of three categories: single dipole, bent dipole/meander, and dual dipole antennas. Single dipole antennas are configured as wire dipoles. Inductive matching stubs are often used to resonate with the IC capacitance; loading structures are used to reduce the linear size of the tag. An example is shown in Figure 20.

Single-dipole tags typically have good read range when oriented along the polarization of the radiation from the reader, but are physically large (close to half a wavelength) and work poorly when cross-polarized. The length of the antennas can be reduced with modest effects on matching by bending the wires; in the extreme case the wires are meandered to produce a tag antenna which is very compact, but a rather inefficient radiator. Such bent or curved dipoles also show some polarization diversity. Tags on the order of 3 cm on a side can be fabricated, but read range is reduced by a factor of 2 to 3 vs. a single-dipole tag.

Cross-polarization sensitivity can also be greatly improved by using more than one independent antenna on the tag—a dual dipole. A representative dual-dipole tag is shown in Figure 21. The two dipole antennas are typically oriented orthogonally in the tag plane. This configuration consumes a lot of area, but provides operation that is almost orientation-independent. Not only can any polarization be received, but the tags can be oriented with one dipole axis pointed towards the reader (rendering that dipole nearly useless) and still receive a signal on the second branch of the antenna. Orientation sensitivity can be reduced at some cost in range for single-dipole tags by using reader antennas that are circularly polarized, but a single-dipole antenna will still become invisible when its axis is directed towards the reader.

SHIP FROM:
Seagull Scientific
15127 N.E. 24th, #333
Redmond, WA 98052

SHIP TO:
Wal-Mart Dist Center #04
1901 Hwy 102 East
Bentonville, AR 72712

SHIP TO POSTAL CODE:
(420) 72712

CARRIER:
Carrier Name
PRO #:123456789
B/L #: 123456789

DC NUMBER
6004

PO :0433124568
WMIT: 001286123

PRINTED ON A DATAMAX RFID PRINTER
DATA WRITTEN TO TAG = 1234567890123456

00 0 1234567898 1

FRONT VIEW

BACK VIEW

Figure 22 · Front and back views of a human-readable label with embedded RFID tag.

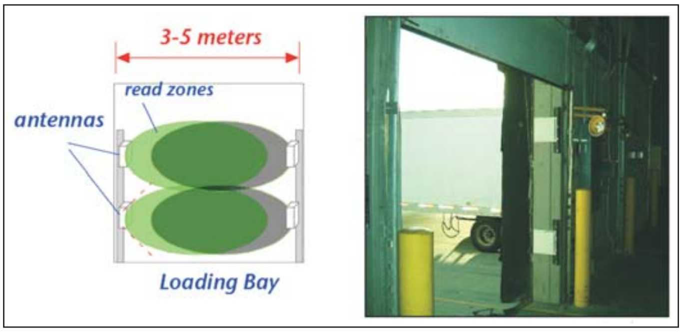

Figure 23 · Schematic depiction of RFID-enabled portal (left) and photograph of a typical installation (right).

Figure 24 · Schematic depiction of rotating x-ray pallet read (left) and photograph of typical installation (right).

Commercial class 1 tags have generally been configured as single dipoles or bent dipoles, whereas class 0 tags are available in both single- and dual-dipole variants. These distinctions are not specified in the standards but are the consequence of design choices made by the respective vendors.

Usage Models and RF Implications

Recent developments in the field have been centered around the use of UHF RFID within the supply chain, and this area is expected to dominate tag usage in the future. We will concentrate on the usage models related to supply chain management in this section, though RFID has many other niche applications that deserve at least a brief mention.

The supply chain lifecycle starts with the application of a tag to the object to be identified. At this point, the object is most often a corrugated cardboard carton containing one or more items destined for eventual sale. For cost reasons only passive RFID tags are used. The RFID tags are generally embedded within a human-readable and bar-coded paper or plastic label which is then attached to the carton using adhesive (Figure 22).

An RFID-enabled label printer is typically used to create the human-readable label while simultaneously programming the embedded RFID tag with the appropriate EPC or other data. This approach is convenient and flexible, though higher in cost per tag than the use of pre-programmed RFID tags. Pre-programmed tags create considerable logistical difficulties in matching the tag EPC to the attached object, and are not widely used. Currently available RFID-enabled printers contain a small-form-factor reader module in an isolated chamber within the printer body. The tags are programmed using a close-coupled proximity antenna. It is important to limit coupling to only one tag at a time, as tags cannot generally be addressed individually prior to being programmed—leakage of radiated fields might cause tags other than the current tag to be programmed in error.

Because of the close-coupled configuration, read range and thus reader output power are not as critical in this application, nor is the ability to resolve multiple tags. Reading speed is also not a key issue, but writing speed is of considerable importance. Writing tags requires more power and considerably more time than reading them, because boost circuits are needed to create the relatively high voltages required for programming the on-board flash memory in which the information is stored. Current printing hardware delivers 1-2 tags per second, with the main limitation on throughput being the process of writing and verifying the RFID tag.

Once cartons have been labeled with an RFID tag, they are often grouped with other cases or boxes and placed on a pallet or other mounting device for shipment and handling. The pallets are transferred using forklift trucks or pallet jacks between trucks or shipping containers, warehousing and storage, and distribution centers. A pallet may contain a few large boxes or a great number of smaller ones, which may be all identical cartons or be a mixture of various types of products. When a pallet is transferred from a manufacturing facility or distribution center to a truck or train for shipment, or when the reverse operation occurs at the receiving dock, it is very useful to obtain an automated record of the contents of the pallet. Traditionally, this was done either through the use of a paper manifest, or by manually scanning the label on each box using a bar code scanner. With RFID tags on each case, it becomes possible to envision automated identification of every case on the pallet as it enters or leaves a facility by way of an RFID-enabled portal (Figure 23). As the pallet passes through the portal region, a sensor such as a photocell is triggered, and a reader with antennas mounted around the portal attempts to read tags within the portal.

There are two general approaches to portal reading. The direct method is to attempt to read every tag on the pallet: this is sometimes known as an X-ray pallet read. Such reads are possible when the contents of the boxes are substantially inactive with respect to the electromagnetic radiation in use. For example, boxes of dry clothing, cereal, or mineral or vegetable oils have little effect on 900 MHz propagation, but women's underclothes may contain support wires which can act as very effective antennas at these frequencies! X-ray reads also become quite difficult if the contents of the boxes are strong RF absorbers or scatterers, such as metallic objects or aqueous fluids. The situation can be improved by empirical screening (hotspot testing) of possible tag locations to find the best placement of the tag on the box for each product type. The most effective approach to X-ray reading is to place the reader at the station where the pallet is shrink-wrapped. At this location, the pallet rotates several times over the course of the wrapping operation, and the reader has a chance to view the pallet from every angle and acquire all the tags (Figure 24). Nevertheless, unless all the tags are outward-facing, it is challenging to obtain high read percentages.

The alternative is to perform a virtual X-ray read, by reading boxes one at a time as they are assembled onto the pallet, then creating a database association of all the EPCs present on a pallet, along with the pallet label itself. Then a successful read of any RFID tag on a pallet, combined with a database lookup, provides the unique EPC of all containers received. Virtual reads greatly simplify the task of automated pallet identification, but do not provide any benefit in reducing shrinkage (theft or loss of individual items).

Portal readers face a number of radio-related challenges. Portal readers need to have a read zone that substantially covers the entry portal (shipping door) of interest. Since the opening can be as much as 3-4 meters wide, read ranges of several meters are important, requiring high reader power and high-gain antennas. In many jurisdictions outside the United States, reader power is limited to 1/2 watt or less, and site licenses may be needed to employ sufficiently high effective isotropic radiated power (EIRP) to reach the whole portal region. In order to read both short and tall pallets, and see both sides of an RF-opaque pallet, at least four antennas are normally used, two on each side of the portal, one high and one low. The antennas are typically multiplexed to a single reader, which means that long antenna cables must be used for some of the antennas; it is important to employ low-loss cabling to avoid dissipating the transmitted power in the cables.

If single-dipole tags are used, polarization is an important issue. Circularly-polarized antennas will read any single-dipole tag whose axis is not directed at the antenna, but at some reduction in range due to the division of power between horizontal and vertical polarizations. Linearly polarized antennas offer improved range if the orientation of the tag can be controlled. Dual-dipole tags offer greatly-reduced polarization sensitivity but at increased cost and larger tag size.

Another key challenge is to properly associate tags read with pallets. Because high power readers are used, sporadic reads must be expected at much longer ranges than the nominal, and at large angles from the pointing direction of the reader antennas, due to antenna sidelobes, reflections from people and objects, and the general complexity of the indoor propagation environment. Pallets may be staged for shipment in close physical proximity to the facility doors. A portal reader may read tags that are not associated with the pallet that is actually entering or leaving the facility through that portal. Solutions include metal screens or shields to minimize portal-to-portal crosstalk, power control, and most importantly middleware provisions for enforcing consistency on the received data.

Pallets will contain many tags, all of which may be within the read zone of one or more antennas simultaneously. The reader must effectively employ the appropriate anti-collision algorithms to manage the shared medium and communicate with all the tags in the read zone. Anti-collision reading is significantly slower than reading an isolated tag, and combined with the need to address the various antennas sequentially and the need (in FCC-like environments) to execute frequency hops, the total time for reading all tags in the field of each antenna may exceed the nominal turn-on time, which is a tradeoff between tag read efficiency and interference.

In a facility with numerous portals (50 doors are not unusual for a large distribution center), interference between readers may become of considerable importance. The distance over which a reader can interfere with another reader is much larger than the tag read range, particularly if high-gain reader antennas view each other

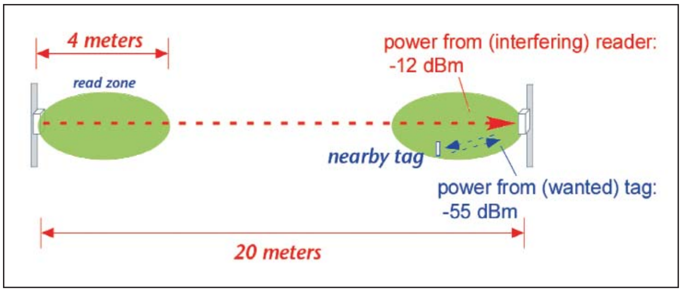

Figure 25 · Exemplary configuration assuming 1 W reader transmit power and 6 dBi antennas, demonstrating that interference range can greatly exceed tag read range.

(Figure 25). The most basic solution to reader-reader interference is to turn off the reader when it is not needed by using sensors for reader activation, as noted above. In the United States, roughly 50 hopping channels are available in the 902-928 MHz ISM band, and interference will be sporadic until tens of readers are in simultaneous operation in a single facility, a situation that is not yet common. However, other jurisdictions provide much narrower bands for RFID operation: ETSI EN 302 208 allows only 3 MHz (865-868), Hong Kong has 8 MHz split into two bands, Singapore allows 5 MHz split into two bands, and Korea allows 5.5 MHz. In these cases interference is much more likely to be a problem in large facilities.

Pallets received into a distribution center are often then broken up into individual boxes, which are transported for sorting by conveyors, at speeds as high as 3 meters/second (600 feet/minute). When these boxes are RFID-labeled, it becomes possible to place readers on the conveyor and automate the sorting operation, improving efficiency and reducing cost (Figure 26). Conveyorized transport is also used in other RFID applications such as airport baggage identification (Figure 27).

Requirements for conveyor reading are significantly different from portal conditions. Because the boxes move rapidly, it is necessary to maintain a very high rate of tag reads: several hundred reads per second are typical. Since only a few tags are likely to be in the read zone at any time, and all tags pass through the read zone, anti-collision provisions are often abandoned in favor of speed, under the presumption that one tag is likely to provide the strongest response at any given time. The optimal antenna setup and read range depend on the details of an individual implementation: antennas oriented along the axis of travel result in a larger effective read zone and a longer time to read each tag, but may also result in tags being read from other areas of the facility. It may be advisable to reduce reader power and direct antennas inwards towards the conveyor, to limit the read zone and avoid spurious tag reads.

As in the case of portal reads, antenna polarization must be matched to the orientation of the tags. Tags might be on the bottom of the box, necessitating a bottom-mounted antenna, it is important to note that metal rollers can act as an array of linear antennas and thus scatter the polarization along their axes, resulting in a linearly-polarized wave after passage through the conveyor even if a circularly-polarized wave was launched. Plastic rollers can be substituted over the antenna if mechanical load tolerances are not exceeded.

Handheld or portable readers (Figure 28) are a very useful resource to supplement fixed readers. Handheld readers can be used instead of a portal reader to record boxes loaded and identify boxes as they are removed; little efficiency is gained relative to bar-coded labels, but customer mandates can be accommodated with minimal initial expense. Handheld readers are also very useful for exception handling: boxes that fail to read at a portal or on a conveyor, misplaced or misoriented labels, identifying boxes of unknown provenance, etc. Handheld readers can be useful for inventory cycle count in storage areas or temporary staging locations, for locating specific cartons in storage, for verifying manifests during assembly, as well as for specialized applications such as tail-to-tail baggage transfer (moving baggage from one airplane to another in an airport without routing it through the terminal).

While supply chain applications are highly visible and likely to expand rapidly in the future, RFID is used in a wide variety of other applications. Large multimodal shipping containers, ubiquitous in modern global trade, can be located and tracked using active tags operating at 433 MHz or 2.45 GHz. The use of active tags provides ranges of hundreds of meters outdoors, making this technology useful in the very large outdoor facilities used for storage and transshipment. Asset tracking can use active or passive tags, depending on whether location services are also desired. Library books can be tracked using HF tags, providing sufficient range for both checkout and theft prevention, and greatly simplifying inventory counting operations. Unique identification using LF or HF short-range tags is also widely used in manufacturing operations. Here RFID tags enable automated management of volume assembly with personalization, used in manufacturing of automobiles and other complex systems. Short range is sufficient since the parts move along well-defined pathways.

Tracking of animals and people can use implanted passive low-frequency tags when only identification is required, or attached active tags when location is important. The latter approach is common for tracking children within theme parks, or prisoners within prisons, as well as for studies of animal behavior in their natural habitat.

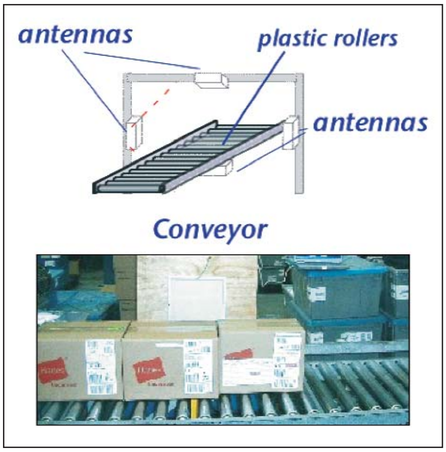

Figure 26 · Schematic depiction of RFID-enabled conveyor (top) and photograph of exemplary supply-chain installation (bottom).

Figure 27 · Conveyorized baggage tagging application.

Figure 28 · Handheld RFID reader using removable PC-card RFID module.

Conclusions

The use of radio-frequency communications to identify and locate physical objects, RFID, has expanded in scope and utility in recent years due to the decreasing cost and increasing capability of electronic devices. The use of a single acronym conceals a considerable diversity of technological approaches, whose strengths and weaknesses dictate differing architecture choices for different applications. RFID systems, particularly those using low-cost passive tags, present special RF and signal processing challenges generally not encountered in other radio systems due to the limitations of the tags and stringent requirements of current and envisioned applications. (As RFID becomes ubiquitous in the ordinary consumer world, it also presents important technological and social challenges related to the privacy and security of data contained therein, which are beyond the scope of this brief introduction.)

We hope that this tutorial will help interested readers become familiar with the field, and clarify the capabilities and limitations of RFID technology.

Acknowledgements

The photographs in Figures 23, 24, 26 and 27 are courtesy of Chris Parkinson of IntegralRFID. The authors would also like to thank John Bellantoni, Nathan Iyer, Andrew Crook, Jim Mravca, Dan Kurtz, Richard Woodburn, Steven Weigand, Kathy Radke, José Hernandez, and Nick McCurdy for helpful discussions, and Leah McLean for assistance with creation of this article.

Bibliography: Web Sites

Numerous web sites provide both current information and background on RFID. Some key sites are:

EPCglobal: www.epcglobalinc.com
US DoD: www.uidsupport.com, www.acq.osd.mil/log/rfid and …/mil/log/logistics_material_readiness/organizations/RFID/
US FDA: www.fda.gov/oc/initiatives/counterfeit/report02_04.html
AutoID Labs archive: www.autoidlabs.org.uk/camwhitepapers.html
International Standards Organization: www.iso.org

Books

The best technical book currently available is *RFID Handbook* (2nd ed., English), by Finkenzeller, Wiley 2004. *RFID Field Guide*, by Bhuptani and Moradpour, Sun 2005, provides updated market information and reviews of the supplier mandates.

Papers

The technical literature in this field is surprisingly limited, though growing rapidly. Articles of interest include:

Rotzoll et. al., “13.56 MHz Organic Transistor Based Rectifier Circuits for RFID Tags,” presented at the 2005 MRS Spring Meeting, San Francisco, CA, March 28-April 1.

U. Kaiser and W. Steinhagen, “A Low-Power Transponder IC for High Performance Identification Systems,” *Custom IC Conference 1994,* 14.4.1, page 355.

S. Masui, E. Ishii, T. Iwawaki, Y. Sugawara and K. Sawada, “A 13.56 MHz CMOS RF Identification Transponder Integrated Circuit with a Dedicated CPU,” *ISSCC99* paper TA9.1.

U. Karthaus and M. Fischer, “Fully Integrated Passive UHF RFID Transponder IC with 16.7 mW Minimum RF

Input Power," *IEEE J. Solid-State Circuits*, 38 #10 p. 1602 (2003).

Ling Lingyu, Zhao Nan, Yang, Xingzi, "New design of RF interface circuits for PICC complying with ISO/IEC14443-2 Type B," *IEEE ASIC Conference 2003,* p. 1037.

M. Usami, "An Ultra Small RFID Chip: m-chip," *2004 IEEE Radio Frequency Integrated Circuits Symposium,* paper MO3D-5, p. 241.

X. Qing and N. Yang, "A Folded Dipole Antenna for RFID," *2004 Antennas and Propagation Symposium*, Monterey, CA.

P. Raumonen, L. Sydanheimo, L. Ukkonen, L, M. Keskilammi, and M. Kivikoski, "Folded dipole antenna near metal plate," *Antennas and Propagation Society International Symposium*, 2003, vol 1 p. 848-851.

L. Ukkonen, D. Engels, L. Sydanheimo, M. Kivikoski, "Planar Wire-Type Inverted-F RFID Tag Antenna Mountable on Metallic Objects," *IEEE Antennas & Propaga-tion Symposium*, Monterey 2004.

P. Foster and R. Burberry, "Antenna Problems in RFID Sys-tems," *IEE RFID Symposium* 1999.

Author Information

Daniel M. Dobkin, Ph.D. is a consultant and former director of technical marketing at WJ Communi-cations. He has worked in the physics of operation of high-speed communications devices and systems for over two decades. He is the author of two books and twenty-five technical publications and is inventor or co-inventor of six U.S. patents. Dr. Dobkin has taught short courses in RFID technology for the Software Development Forum, San Jose State University, and the Singapore Manufacturer's Federation. He holds both a Ph.D. and M.S. degree in Applied Physics from Stanford University, and a B.S. from the California Institute of Technology.

Titus Wandinger is a strategic marketing engineer for WJ Communications and has almost 20 years of experience designing and developing high performance radio and semiconductor products. Early in his career he developed high performance semiconductor devices for advanced receiver applications. Subsequently he led the circuit development group for semiconductor products. Since joining Strategic Marketing, he has been involved in promoting the growth of RFID applications within WJ. He has also served on the EPC Standards Group for the development of next generation RFID standards. Mr. Wandinger holds an MS from Stanford University in Applied Physics and a BSEE from Cornell University.