The history of RFID

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Whether we realize it or not, radio frequency identification (RFID) is an integral part of our life. RFID increases productivity and convenience. RFID is used for hundreds, if not thousands, of applications such as preventing theft of automobiles and merchandise; collecting tolls without stopping; managing traffic; gaining entrance to buildings; automating parking; controlling access of vehicles to gated communities, corporate campuses and airports; dispensing goods; providing ski lift access; tracking library books; buying hamburgers; and the growing opportunity to track a wealth of assets in supply chain management. RFID technology is also being pressed into service for use in U.S. Homeland Security with applications such as securing border crossings and intermodal container shipments while expediting low-risk activities.

RFID is a term coined for short-range radio technology used to communicate mainly digital information between a stationary location and a movable object or between movable objects. A variety of radio frequencies and techniques are used in RFID systems. RFID is generally characterized by use of simple devices on one end of the link and more complex devices on the other end of the link. The simple devices (often called tags or transponders) are small and inexpensive, can be deployed economically in very large numbers, are attached to the objects to be managed, and operate automatically. The more complex devices (often called readers, interrogators, beacons) are more capable and are usually connected to a host computer or network. Radio frequencies from 100 kHz to 10 GHz have been used.

The tags are usually built using CMOS circuitry while other technologies can be used such as surface acoustic wave (SAW) devices or tuned resonators. Tags can be powered by a battery or by rectification of the radio signal sent by the reader. Tags can send data to the reader by changing the loading of the tag antenna in a coded manner or by generating, modulating, and transmitting a radio signal. A variety of modulation and coding techniques have been used. RFID systems can be read-only (data is transferred only in one direction, from the tag to the reader) or read-write (two-way communication).

A typical RFID system can use the principle of modulated backscatter (see Fig. 1). In this type of RFID system, to transfer data from the tag to the reader, the reader sends an unmodulated signal to the tag. The tag reads its internal memory of stored data and changes the loading on the tag antenna in a coded manner corresponding to the stored data. The signal reflected from the tag is thus modulated with this coded information. This modulated signal is received by the reader, demodulated using a homodyne receiver, and decoded and output as digital information that contains the data stored in the tag. To send data from the reader to the tag, the reader amplitude modulates its transmitted radio signal. This modulated signal is received by the tag and detected with a diode. The data can be used to control operation of the tag, or the tag can store the data. A simple diode detector allows the detection circuitry in the tag to be simple and consume little power.

Mankind's use and understanding of electricity, magnetism, and electromagnetics in very early times was limited to his eyesight, observation of electrostatic discharge (don't stand under a large tree during a lightning storm), and the magnetic properties of lodestones. Early applications probably included making light with fire, use of mirrors for signaling, and use of lodestones for navigation.

Scientific understanding progressed very slowly until about the 1600s. From the 1600s to 1800s there was an explosion of observational knowledge of electricity, magnetism, and optics accompanied by a growing base of mathematically related observations. The 1800s marked the beginning of the fundamental understanding of electromagnetic energy. In 1846, English experimentalist Michael Faraday proposed that both light and radio waves are a form of electromagnetic energy. In 1864, Scottish physicist James Clerk Maxwell published his theory on electromagnetics. In 1887, German physicist Heinrich Rudolf Hertz confirmed Maxwell's electromagnetic

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theory and produced and studied electromagnetic waves (radio waves). Hertz is credited as the first to transmit and receive radio waves, and his demonstrations were followed quickly by Aleksandr Popov in Russia.

In 1896, Guglielmo Marconi demonstrated the first successful transmission of radiotelegraphy across the Atlantic, and the world would never be the same.

Forward to 20th century

In 1906, Ernst F.W. Alexanderson demonstrated the first continuous wave (CW) radio generation and transmission of radio signals. This achievement marks the beginning of modern radio communication, where all aspects of radio waves are controlled. The early 20th century was considered the birth of radar. The work in radar during World War II was as significant a technical development as the Manhattan Project. Radar sends out radio waves for detecting and locating an object by the reflection of the radio waves. This reflection can determine the position and speed of an object. Radar's significance was quickly understood by the military, so many of the early developments were shrouded in secrecy.

Since one form of RFID is the combination of radio broadcast technology and radar, it is not unexpected that the convergence of these two radio disciplines and the thoughts of RFID occurred on the heels of the development of radar.

Genesis of an idea

An early, if not the first, work exploring RFID is the landmark paper by Harry Stockman, "Communication by Means of Reflected Power," published in 1948. Stockman stated "Evidently, considerable research and development work has to be done before the remaining basic problems in reflected-power communication are solved, and before the field of useful applications is explored."

Thirty years would pass before Stockman's vision would reach fruition. Other developments were needed: the transistor, the integrated circuit, the microprocessor, development of communication networks, and changes in ways of doing business. The success of RFID would have to wait a while.

Much has happened in the 57 years since Stockman's work. The 1950s were an era of exploration of RFID techniques following technical developments in radio and radar in the 1930s and 1940s. Several technologies related to RFID were being explored such as the long-range transponder systems of "identification, friend, or foe" (IFF) for aircraft. Developments of the 1950s include such works as D.B. Harris's "Radio transmission systems with modulatable passive responder." The wheels of RFID development were turning.

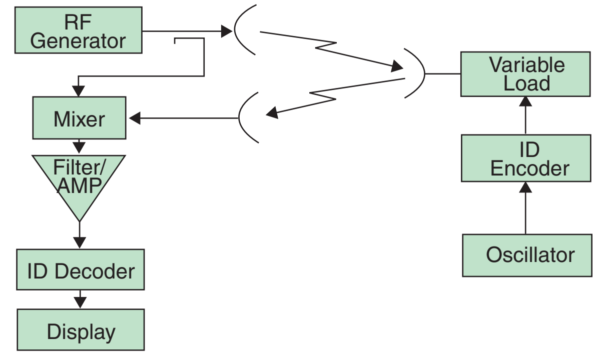

Fig. 1 Functional blocks for reading data from a backscatter RFID tag. The reader is on the left, and the tag is on the right.

RFID becomes reality

The 1960s were the prelude to the RFID explosion of the 1970s. R.F. Harrington studied the electromagnetic theory related to RFID in his papers including "Theory of Loaded Scatterers" in 1964. Inventors were busy with RFID-related inventions such as Robert Richardson's "Remotely activated radio frequency powered devices," and J. H. Vogelman's "Passive data transmission techniques utilizing radar echoes."

Commercial activities were beginning in the 1960s. Sensormatic and Checkpoint were founded in the late 1960s. These companies, with others such as Knogo, developed electronic article surveillance (EAS) equipment to counter the theft of merchandise. These types of systems are often use 1-b tags; only the presence or absence of a tag could be detected, but the tags could be made inexpensively and provided effective antitheft measures. These types of systems used either microwave (generation of harmonics using a semiconductor) or inductive (resonant circuits) technology. EAS is arguably the first and most widespread commercial use of RFID. Tags containing multiple bits were generally experimental in nature and were built with discrete components. While single-bit EAS tags were small, multibit tags were the size of a loaf of bread, constrained in size by the dictates of the circuitry.

In the 1970s developers, inventors, companies, academic institutions, and government laboratories were actively working on RFID, and notable advances were being realized at research laboratories and academic institutions such as Los Alamos Scientific Laboratory, Northwestern University, and the Microwave Institute Foundation in Sweden. An early and important development was the Los Alamos work that was presented by Alfred Koelle, Steven Depp, and Robert Freyman, "Short-Range Radio-Telemetry for Electronic Identification Using Modulated Backscatter," in 1975. This development signaled the beginning of practical, completely passive tags with an operational range of tens of meters. Large companies were also developing RFID technology, such as Raytheon's Raytag in 1973 and Richard Klensch of RCA developing an electronic identification system in 1975.

The Port Authority of New York and New Jersey was also testing systems built by General Electric, Westinghouse, Philips, and Glenayre. Results were favorable, but the first commercially successful transportation application of RFID, electronic toll collection, was not yet ready for prime time.

The 1970s were characterized primarily by developmental work. Intended applications were for animal tracking, vehicle tracking, and factory automation. Examples of animal tagging efforts were the microwave systems at Los Alamos and Identronix and the inductive systems in Europe. Interest in animal tagging was high in Europe. Alfa Laval, Nedap, and others were developing RFID systems.

Transportation efforts included work at Los Alamos and by the International Bridge Turnpike and Tunnel Association (IBTTA) and the United States Federal Highway Administration. The latter two sponsored a conference in 1973 that concluded there was no national interest in developing a standard for electronic vehicle identification. This is an important decision since it would permit a variety of systems to develop, which was good, because RFID technology was in its infancy. Research efforts continued as well. R.J. King authored a book about microwave homodyne techniques in 1978. This book is an early compendium of theory and practice used in backscatter RFID systems.

Tag technology had improved with reductions in size and improvements in functionality. The key to these advancements was the use of low-voltage, low-power CMOS logic circuits. Tag memory utilized switches or wire bonds and had improved with use of fusible link diode arrays by the end of the decade.

The 1980s became the decade for full implementation of RFID technology, though interests developed somewhat differently in various parts of the world. The greatest interests in the United States were for transportation, personnel access, and, to a lesser extent, animals. In Europe, the greatest interests were for short-range systems for animals and industrial and business applications, though toll roads in Italy, France, Spain, Portugal, and Norway were equipped with RFID. A key to the rapid expansion of RFID applications was the development of the personal computer (PC) that allowed convenient and economical collection and management of data from RFID systems.

In the Americas, the Association of American Railroads and the Container Handling Cooperative Program were active with RFID initiatives. Tests of RFID for collecting tolls had been going on for many years, and the first commercial application began in Europe in 1987 in Norway and was followed quickly in the United States by the Dallas North Turnpike in 1989. Also during this time, the Port Authority of New York and New Jersey began commercial operation of RFID for buses going through the Lincoln Tunnel. RFID was finding a home with electronic toll collection, and new players were arriving daily.

Tags were now being built using custom CMOS integrated circuits combined with discrete components for microwave tags. EEPROM became the nonvolatile memory of choice, permitting the large-scale manufacture of identical tags that could be individualized through programming. These advancements lead to further reductions in the size of tags and increase in functionality (see Fig. 2). The constraint of required antenna size was now becoming important in determining the size of tags.

The 1990s

The 1990s were a significant decade for RFID since it saw the wide scale deployment of electronic toll collection in the United States and the installation of over 3 million RFID tags on rail cars in North America. Important deployments included several innovations in electronic tolling. The world's first open highway electronic tolling system opened in Oklahoma in 1991, where vehicles could pass toll collection points at highway speeds, unimpeded by a toll plaza or barriers and with video cameras for enforcement. The first combined toll collection and traffic management system was installed in the Houston area by the Harris County Toll Road Authority in 1992. Also a first was the system installed on the Kansas turnpike using readers that could also operate with the different-protocol tags of their neighbor to the south, Oklahoma. Georgia would follow, upgrading their equipment with readers that could communicate with tags using a new protocol as well as their existing tags. In fact, these two installations were the first to implement a multiprotocol capability in electronic toll collection applications.

In the northeastern United States, seven regional toll agencies formed the E-Z Pass Interagency Group (IAG) in 1990 to develop a regionally compatible electronic toll collection system. This system is the model for using a single tag and single billing account per vehicle to access highways and bridges of several toll authorities.

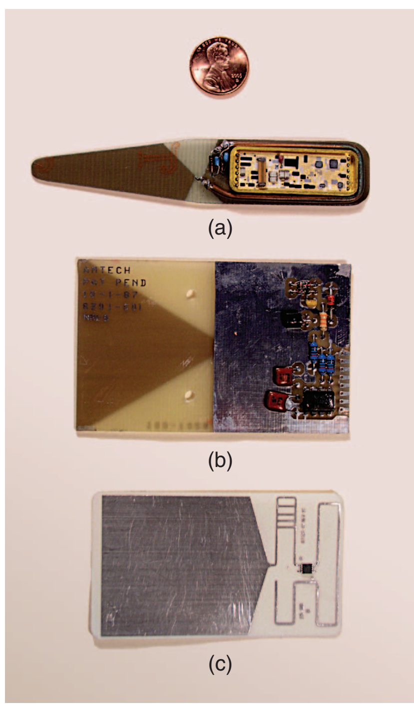

Fig. 2 Evolution of RFID tags compared in size to a penny. (a) A 12-b read-only tag built using CMOS logic chips and hybrid thick film, circa 1976. Circuitry covers half of tag area. (b) A 128-b read-only tag built using a custom CMOS integrated circuit with off-chip components, circa 1987. Circuitry covers a quarter of tag area. (c) A 1024-b read-write tag built using a single custom CMOS integrated circuit, circa 1999. Circuitry covers an insignificant portion of the tag area.

Interest was also keen for RFID applications in Europe during the 1990s. Both microwave and inductive technologies were finding use for toll collection, access control, and a wide variety of other applications in commerce.

A new effort underway was the development of the Texas Instruments (TI) TIRIS system, used in many automobiles for control of the starting of the vehicle engine. The TIRIS system (and others such as from Mikron, now a part of Philips) developed new applications for dispensing fuel, gaming chips, ski passes, and vehicle access.

Additional companies in Europe were becoming active in the RFID race as well with developments including Microdesign, CGA, Alcatel, Bosch and the Philips spinoffs of Combitech, Baumer, and Tagmaster. A pan-European standard was needed for tolling applications in Europe, and many of these companies (and others) were at work on the CEN standard for electronic tolling.

Tolling and rail applications were also appearing in many countries including Australia, China, Hong Kong, Philippines, Argentina, Brazil, Mexico, Canada, Japan, Malaysia, Singapore, Thailand, South Korea, South Africa, and Europe.

With the success of electronic toll collection, other advancements followed such as the first multiple use of tags across different business segments. Now, a single tag (with dual or single billing accounts) could be used for electronic toll collection, parking lot access and fare collection, gated community access, and campus access. In the Dallas–Ft. Worth metroplex, a first was achieved when a single TollTag on a vehicle could be used to pay tolls on the North Dallas Tollway, for access and parking payment at the Dallas/Ft. Worth International Airport, the nearby Love Field, and several downtown parking garages as well as access to gated communities and business campuses.

Research and development didn't slow down during the 1990s with new technological developments expanding the functionality of RFID. For the first time, useful microwave Schottky diodes were fabricated on a regular CMOS integrated circuit. This development permitted the construction of microwave RFID tags that contained only a single integrated circuit, a capability previously limited to inductively coupled RFID transponders. Books began to appear devoted specifically to RFID technology. Klaus Finkenzeller wrote one of the first in 1999.

With the growing interest of RFID into the item management arena and the opportunity for RFID to work along side bar code, it becomes difficult in the later part of this decade to count the number of companies who enter the marketplace. Many have come and gone, many are still here, many have merged, and there are many new players ... it seems almost daily!

Back to the future: The 21st century

The 21st century opens with the smallest microwave tags built using, at a minimum, two components: a single custom CMOS integrated circuit and an antenna. Tags could now be built as sticky labels, easily attached to windshields and objects to be managed. The use of RFID for electronic toll collection had expanded in the United States to 3,500 lanes of traffic by 2001. EEPROM remained the nonvolatile memory of choice. The search continues for a fast nonvolatile memory suited to the requirements of RFID. The size of tags is now limited by the constraints of the antenna. The design of suitable antennas and the search for better nonvolatile memory are continuing design challenges.

The impact of RFID is lauded regularly in mainstream media, with the use of RFID slated to become even more ubiquitous. The growing interest in telematics, article tracking, and mobile commerce will bring RFID even closer to the consumer. The U.S. Federal Communications Commission (FCC) allocated spectrum in the 5.9 GHz band for a vast expansion of intelligent transportation systems with many new applications and services proposed. But the equipment required to accommodate these new applications and services will necessitate advancements beyond the "traditional" RFID technology. This next generation of short-range communication systems between roadside and vehicle are presently being standardized within the IEEE and are based on wireless LAN techniques.

Supply chain management and article tracking are RFID application areas that have grown rapidly spurred by the technical breakthrough of the late 1990s to incorporate microwave diodes in silicon on the same die as the tag circuitry. This development allows a reduction in the size of circuitry, reduction in cost of tags, increased functionality, and increased reliability. The AutoID center was organized at the Massachusetts Institute of Technology to bring together RFID manufacturers, researchers, and users to develop standards, perform research, and share information for supply chain applications. EPC Global has assumed the task of standards for this application area. The International Standards Organization also has very active standards activities for a variety of application areas.

The Decades of RFID

Decade	Event
1940–1950	Radar refined and used, major World War II development effort. RFID invented in 1948.
1950–1960	Early explorations of RFID technology, laboratory experiments.
1960–1970	Development of the theory of RFID. Start of applications field trials.
1970–1980	Explosion of RFID development. Tests of RFID accelerate. Very early adopter implementations of RFID.
1980–1990	Commercial applications of RFID enter mainstream.
1990–2000	Emergence of standards. RFID widely deployed. RFID becomes a part of everyday life.
2000–	RFID explosion continues

The pace of developments in RFID continues to accelerate. The future looks very promising for this technology. The full potential also requires advancements in other areas as well such as development of applications software; careful development of privacy policies and consideration of other legal aspects; development of supporting infrastructure to design, install, and maintain RFID systems; and other such activities now that RFID has truly entered the mainstream.

At first glance, the concept of RFID and its application seems simple and straightforward. But in reality, the contrary is true. RFID is a technology that spans systems engineering, software development, circuit theory, antenna theory, radio propagation, microwave techniques, receiver design, integrated circuit design, encryption, materials technology, mechanical design, and network engineering, to mention a few. Increasing numbers of engineers are involved in the development and application of RFID, and this trend will likely continue. At present, the shortage of technical and business people trained in RFID is hampering the growth of the industry.

As we create our future, and it is bright, let us remember, "Nothing great was ever achieved without enthusiasm" (Ralph Waldo Emerson). We have a great many developments to look forward to, history continues to teach us that.

Read more about it

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About the author

Jeremy Landt is one of the scientists from Los Alamos National Laboratory that developed RFID for the federal government. As TransCore's chief scientist, he is responsible for leading the technical developments of RFID systems. In 1984, he was one of the five cofounders of Amtech Corporation and served as vice president of research and development. He served on the Amtech board of directors from May 1989 to August 1998. He has authored more than 60 technical papers and been awarded 16 U.S. patents. Before joining Amtech, he worked for nine years at the Los Alamos National Laboratory in New Mexico. He earned a Ph.D. in electrical engineering from Stanford University and a master of science degree and a bachelor of science degree in electrical engineering from the South Dakota School of Mines and Technology.