1 Introduction to RFID history and markets

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The market for radio frequency identification (RFID) technology is growing rapidly, with significant opportunities to add value, but also, because of the challenging issues that are identified in the chapters that follow, many opportunities for failure. This book brings together pioneering RFID academic research principals to analyze engineering issues that have hampered the deployment of RFID and to share "best practices" learnings from their work, building on the tradition of the Auto-ID Labs. The Auto-ID Labs consortium of leading universities around the world includes Auto-ID Labs at Cambridge University, Fudan University, Keio University, the University at St. Gallen and the ETH Zürich, the University at Adelaide and, most recently, the ICU, South Korea.[1] The principal investigators represented here have conceived, obtained funding for, and executed research projects using RFID technology. The authors share their experience in the design, test, prototyping, and piloting of RFID systems, both to help others avoid "reinventing the wheel" and to set the stage for what is next in RFID.

Because RFID technology has evolved from proprietary systems operating at different frequencies in jurisdictions with different RF regulatory restrictions, most RFID work has been divided into communities operating at one frequency or another. In *RFID Technology and Applications* we bring together principal investigators with experience in passive RFID systems across a range of frequencies including UHF 860–960 MHz (EPC GenII/ISO 18000–6c) and HF 13.56 MHz (ISO 18000-3),[2] but also, breaking with precedent, we include experts

[1] The Auto-ID Labs are the leading global network of academic research laboratories in the field of networked RFID. The labs comprise seven of the world's most renowned research universities located on four different continents (www.autoidlabs.org).

[2] ISO specification for RFID under the standard 18000-1 Part 1 – Generic Parameters for the Air Interface for Globally Accepted Frequencies at frequencies per below can be obtained from http://www.iso.org/iso/en/CombinedQueryResult.
18000-2 Part 2 – Parameters for Air Interface Communications below 135 kHz
18000-3 Part 3 – Parameters for Air Interface Communications at 13.56 MHz
18000-4 Part 4 – Parameters for Air Interface Communications at 2.45 GHz
18000-5 Part 5 – Parameters for Air Interface Communications at 5.8 GHz (withdrawn)

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in active (with power) RFID systems. The inclusion of active RFID with passive systems allows us to explore a wider range of technologies for how one might best add "real-world awareness," such as location and sensor data, to the information about identified objects – both of which are high-growth markets, as cited in the Preface. Researchers gathered in this collection of essays have been selected for their experience as principal investigators and RFID lab directors and from their participation in the RFID Academic Convocations that are being held around the world with industry and government leaders to explore issues requiring greater research collaboration.[3]

This chapter provides an historical introduction to RFID together with an overview of the standards and regulatory frameworks that cross frequencies, protocols, and processes to govern how we engineer RFID systems to operate in different jurisdictions. Recent breakthroughs in global standards and regulatory initiatives in European and Asian countries have freed unlicensed UHF radio spectrum for use by RFID systems, making this a seminal moment to examine new system design possibilities. During the spring of 2007 the conditional approval of UHF as well as HF frequencies for RFID applications in China and Europe, the adoption of a variety of technical standards for passive and active RFID systems into the International Standards Organization (ISO) process, the availability of much of this technology under Reasonable and Non Discriminatory Licensing (RAND – see Section 15.7) terms, and the release of the Electronic Product Code Information Services (EPCIS) software specifications for exchanging data about products from EPCglobal all promise to make it possible to communicate more effectively about the condition and location of products. The chapters that follow explore the underlying technology and growing markets for asset-tracking and cold-chain and condition-based monitoring across entire supply chains and product lifecycles.

The technology chapters begin with a deep dive into the design of low-power passive and active RFID transponders (tags) and RF performance in near-field and far-field modes over HF and UHF frequencies. The "Swiss cheese effect" of RF "null" zones caused by multipath effects, as well as "ghost tags," the bane of indoor RF systems, are introduced by Hao Min, Director of the Auto-ID Lab at Fudan University in Shanghai (Ch. 2), together with recommendations for addressing these issues at a tag and, in subsequent chapters, at the system and supply chain network level. The RFID applications chapters of this book present hands-on research experience of principal investigators in specific markets and illustrate the promise they see for changing the way businesses is done. "How does the world change," observes Hao Min while working on his contribution to this

18000-6 Part 6 – Parameters for Air Interface Communications at 860 to 960 MHz
18000-7 Part 7 – Parameters for Air Interface Communications at 433 MHz

[3] The RFID Academic Convocation co-hosted by the Auto-ID Lab at MIT brings together RFID research principals, leaders from industry and government, and technology providers to address research issues surrounding the implementation of RFID (http://autoid.mit.edu/CS/blogs/convocations/default.aspx).

book, "when the 'Internet of things' contains a profile for every object. If we contrast this to the internet today, information about people and events are recorded and Google is used to search information about people and events. If the information (profile) of every object (include people) is recorded, what will the internet be like?"

One of the first issues RFID project managers face is the lack of diagnostic tools to characterize RF environments and RF tag performance on specific products, short of working within a fully instrumented anechoic chamber and using finite state analysis to simulate indoor RF propagation fields. As Larry Bodony, one of the members of the MIT Enterprise Forum RFID Special Interest Group commented recently on his experience implementing RFID container tracking systems with Lockheed Martin/Savi Networks, "RFID is like an Ouija Board, where you address one RF problem and another issue pops up somewhere else" [1].

Like the Ouija Board, RFID's roots can be traced to the period of spiritualist practices in the mid nineteenth century and to Maxwell, who first predicted the existence of electromagnetic waves. In the chapters that follow we ask the following question: "what are the RFID engineering issues that need to be addressed to fulfill the promise of increased visibility and collaboration?" As an organizing principle for the chapters that follow, control systems methodology is introduced as an approach to addressing RFID engineering issues. The theme of control systems methodology for systems design spans recent work by co-editors Sanjay Sarma, co-founder of the Auto-ID Center, on "Six Sigma Supply Chains" [2], as well as by John Williams, Director of the Auto-ID Labs at MIT, on "Modeling Supply Chain Network Traffic" (Ch. 7).

1.1 Market assessment

The sales of passive RFID UHF tags conforming to international interoperability standards for supply chain applications are not yet growing as quickly as anticipated, despite, or perhaps because of, their low price – under 15¢ for EPC GenII/ISO 18000-6c transponders (tags). At the 2007 Smart Labels Conference in Boston, Raghu Das, CEO of IDTechEx, estimated that sales of RFID tags for 2006 would total 1.3 billion tags. As cited in the preface "about 500 million RFID smart labels will be used for pallet and case level tagging but the majority will be used for a range of diverse markets from baggage and passports to contactless payment cards and drugs."[4]

The overall number of RFID tag unit sales is estimated to grow by 100% this year, in conjunction with costs that are dropping by 20% or more per year. The range of technologies is also growing at a rapid pace, both for low-cost and for

[4] RFID Smart Labels 2007 – IDTechEx, February 20–23, 2007, Boston Marriott, Boston, MA (http://rfid.idtechex.com/rfidusa07/en/RFIDspeakers.asp).

high-end tag functionality. RFID tags as a class of low-cost sensors are evolving to include more or less additional intelligence (processors, memory, embedded sensors) on a variety of platforms (from semiconductor inlays and MEMs to inorganic and organic materials that form thin film transistor circuits – TFTCs) across a variety of frequencies (UHF, HF, LF) and protocols (802.11, Bluetooth, Zigbee, EPC GenII).

In meetings with industry stakeholders, government representatives, and academic researchers in search of better ways to communicate about products at the RFID Academic Convocations, one is struck by the diversity of applications for RFID. Researchers have discussed applications from tracking the condition of containers across oceans to production control in semiconductor "lights out" factories, from keeping tabs on draft beer kegs for pubs in Britain to monitoring sales promotions compliance across retail distribution networks.

In spite of the overall market growth for tagging products, it is still difficult to communicate outside "the four walls" of an enterprise today. Most RFID systems have been "closed loop" proprietary technologies, while the promise of enhanced supply chain visibility and eBusiness collaboration using low-cost "open loop" interoperable passive UHF RFID tags is still hampered by technical issues as are explored in depth herewith. While the passive UHF RFID tags envisioned at MIT were restricted by design to minimize cost and therefore contained just enough memory to store a unique identifier the length of an EPC code, RFID tag manufacturers continue to develop a wide range of systems operating at various frequencies and combinations thereof. Suppliers are also adding memory and processing power for storing and processing additional information about the condition, maintenance history, and/or location of individually tagged assets. We will learn from the authors how far RFID technology has come in these applications, in an overall market that promises to deliver more tags in the next year than in the prior sixty years since RFID was invented, and what new applications they are exploring that may change the world.

1.2 Historical background

The history of radio frequency engineering can be traced to 1864 when James Clerk Maxwell predicted the existence of electromagnetic waves, of which microwaves are a part, through Maxwell's equations. By 1888, Heinrich Hertz had demonstrated the existence of electromagnetic waves by building an apparatus that produced and detected microwaves in the UHF region, the radio frequency selected by the Auto-ID Center at MIT for its passive RFID initiative a century and a half later. From Dr. Jeremy Landt's *Shrouds of Time; the History of RFID*, we learn that "[Maxwell's] design used horse-and-buggy materials, including a horse trough, a wrought iron point spark, Leyden jars, and a length of zinc gutter whose parabolic cross-section worked as a reflection antenna." [3].

Radio frequencies, like other physical signals in nature, are analog, as is also the case for voltage, current, pressure, temperature, and velocity. Radio frequency waves and radar radiation connect interrogators and tags via "inductive coupling" or "backscatter coupling" as will be analyzed in depth by Marlin Mickle in "Resolution and Integration of HF & UHF" (Ch. 4). The first RFID applications were developed in conjunction with radar technology at the height of the Second World War, for Identification Friend or Foe (IFF) systems, where the RF transponder (tag) and interrogator (reader) were designed to detect friendly airplanes. [4] A precursor to passive RFID was the electronic article surveillance (EAS) systems deployed in retail stores in the 1970s that used dedicated short-range communication (DSRC) RF technology for anti-theft detection.

Auto-ID RFID technology builds on automated data capture (AIDC) barcode standards for identifying products that, together with the standardization of shipping container dimensions, have so dramatically lowered the cost of transportation in recent decades [5]. Companies that seized the opportunity to optimize their supply chains with this technology have become some of the largest companies in the world, including such retailers as Wal-Mart, Metro, Target, and Carrefour. The best-known and most widespread use of AIDC barcode technology has been in consumer products, where the Universal Product Code (UPC) was developed in response to grocery industry requirements in the mid 1970s [6] [7]. Where barcodes are widely used in these networks today, RFID systems are now being installed to expedite non-line-of-sight data capture using RF to read the electronic product code (EPC) on RFID tags.

One area where history can help us to avoid "reinventing the wheel" is in human resources planning for what RF background is useful for implementing low-power RFID systems today. In my search for domain expertise in this area I was surprised to learn, upon meeting two leading RF experts, Peter Cole, Ph.D., the Director of the Auto-ID Lab at Adelaide University, whose work was instrumental in the initial MIT Auto-ID Center UHF specifications, and Marlin Mickle, Ph.D., the Nickolas A. DeCecco Professor and Director of the RFID Center of Excellence at the University of Pittsburgh, that they are both septuagenarians. They were students during the Second World War when radar technology was saving lives during the Blitz bombardments against London. Radar engineers are familiar with the multipath effects that cause ghost targets to appear, phenomena that haunt RFID data acquisition to this day. By contrast, the RF engineers who have worked in more recent RF domains such as cellular telephony and wireless LANs are accustomed to working at much higher power levels and with more host processing capabilities in cell phones than are present in tiny RFID tags. This insight was confirmed by SAAB executives[5] in a meeting at the MIT Auto-ID Labs (April 10, 2007), who related their success in bringing radar technicians from the airplane manufacturing side of the business to design their first EPC GenII/ISO 18000-6c RFID infrastructure.

[5] Goran Carlqvist, Lars Bengtsson, and Mats Junvikat.

1.3 Adoption of the Auto-ID system for the Electronic Product Code (EPC)

I have the good fortune of writing this introduction from the perspective of the MIT Auto-ID Labs, successor to the Auto-ID Center, where, with input from sponsors Gillette, Proctor and Gamble, and the Uniform Code Council (now GS-1), the specifications for a passive UHF RFID Electronic Product Code system were conceived and where current research is expanding the boundaries of the "internet of things." In the 2001 white paper *The Networked Physical World, Proposal for Engineering the Next Generation of Computing, Commerce and Automatic Identification*, co-authors Sanjay Sarma, Ph.D., David Brock, Ph.D., and Kevin Ashton [8] proposed a system for the Electronic Product Code. The name for the language to communicate the whereabouts of an object in time and place was the Physical Markup Language (PML) [9]. The specifications for UHF passive tags and RFID interrogators developed at the Auto-ID Center were subsequently licensed by EPCglobal, a standards body that was formed from the article-numbering barcode associations around the world, to promote the use of RFID in commerce.

As Alan Haberman, an early proponent of barcodes who served on the Board of Governors for the new EPCglobal association, reminded us in his review of this introductory chapter, the nature of the technology transfer process for the Auto-ID system from academia to industry differed from other technology licensing agreements. In this case, the licensor was GS-1, an organization that had grown from the adoption by the grocery industry of a standard for barcodes in 1973 – the Universal Product Code (UPC). Today GS-1 is a not-for-profit organization representing 1.2 million company users in 130 nations that develops, promotes, and governs, through the participation of its members, standards for automatic identification of product, location, and process worldwide. GS-1's investment in RFID reflects their view of the sea change in technology for identification that RFID represents and their commitment to supporting the maturation and technology transfer to industrial and commercial users around the globe. GS-1's commitment to financing the development of a new organization, EPCglobal, its investment in spreading the word and building that organization, and the initial five-year commitment of $2,000,000 per annum to the Auto-ID Labs consortium led by MIT for ongoing research are some of the elements that have positioned RFID technology for worldwide adoption.

In addition to the challenging physics of generating low-power electromagnetic UHF signals to wake up passive RFID tags to transmit their ID in the original MIT research, a major hurdle in establishing the Auto-ID system, whereby RFID readers in one country could read RFID tags from another, began with ensuring the availability of common unlicensed radio frequencies across national jurisdictions. Starting with frequency regulations, freeing up the 860–960 MHz UHF spectrum for EPC GenII/ISO-18000-6c RFID transmissions has presented a challenge, both in Europe, where regulatory limits to transmission power and "listen before talk" restrictions hampered UHF RFID performance, and in Asian

countries, where these frequencies were licensed for other uses. A great number of individuals from industry and governmental organizations around the world have contributed to opening this unlicensed spectrum for the use of RFID, including the Research Directors of the Auto-ID Labs, who have been instrumental in their respective countries in establishing a constructive dialogue with government and industry on interoperable standards for RFID.

In May of 2004, following the formation of the Auto-ID Labs, David Brock, Ph.D., a co-founder of the Auto-ID Center, and I were invited to participate in the Forum on eBusiness Interoperability and Standardization organized by Dr. David Cheung, Director of the University of Hong Kong's Centre for E-Commerce Infrastructure Development (CECID).[6] One outcome was MIT Auto-ID Labs' support for the successful application by Ms. Anna Lin, President of the Hong Kong Article Numbering Association, for a $1.8M RFID pilot grant to track goods manufactured in southern China's Pearl River Delta funded by the Hong Kong Innovation & Technology Commission [10]. Building on the success of this project, the Japanese Ministry of Economics, Trade, and Industry (METI) is sponsoring cross-border RFID pilots between China and Japan. One of the early research participants, Dr. S. K. Kwok, Project Fellow of the Hong Kong Polytechnic University, presented his research findings in "RFID for Enhancing Shipment Consolidation Processes" at the RFID Academic Convocation in Shanghai [11]. The Auto-ID Labs at MIT support international standards through hosting groups, such as a recent visit by the Coordination Program of Science and Technology Project of the Japan Science and Technology Agency, as well as leading academic researchers in healthcare and logistics and advisors to government agencies on technology strategy. One recurrent theme that we hear from different national technology planners is how much better off the world is as a result of achieving consensus around IEEE 802.11 WiFi protocols for unlicensed RF data communications, and how the EPCglobal GenII/ISO-18000-6c specifications for passive UHF RFID systems have similar promise.

Through hosting the RFID Academic Convocations noteworthy exchanges with the Auto-ID Labs have included Dr. Zhang Zhiwen of the Ministry of Science and Technology (MOST) and the RFID Lab at the Chinese Academy of Sciences (CASIA) in Beijing,[7] whose initial visit to MIT in October of 2005 led to his presentation of the Chinese Public Service Infrastructure project at the first RFID Academic Convocation (Cambridge, MA, January 23–4, 2006) [12]. Subsequent research collaboration sponsored by SAP Research using ISO 18000-6c systems in a secure supply chain is being explored both at the MIT Auto-ID Labs (Ch. 7) and directly with the RFID Laboratory at CASIA and with Haier Corporation, the world's biggest volume producer of white goods, in Qingdao,

[6] Forum on e-Business Interoperability and Standardization, organized with Jon Bosak, chair of the OASIS Universal Business Language Technical Committee (May 14, 2004, Hong Kong University, Hong Kong) (http://www.cecid.hku.hk/forum/file/ebusiness-eng.doc).

[7] http://www.rfidinfo.com.cn.

Shandong Province, People's Republic of China. The China Ministry of Science and Technology and Chinese Academy of Sciences (CASIA), together with Hao Min, Director of the Auto-ID Labs at Fudan University, co-sponsored the third RFID Academic Convocation (Shanghai, October 29–30, 2006) [13].

The participation by Dr. Peter Friess of the European Commission DGIT, with his contribution on "Networked Enterprise & Radio Frequency Identification (RFID)," in the first RFID Academic Convocation at MIT was equally noteworthy in that it led to the EU's participation in the Shanghai Convocation and subsequently to its hosting the RFID FORUM EUROPE 2007/RFID Academic Convocation (Brussels, March 13–14, 2007). Henri Barthel, Technical Director of GS-1 Europe and Coordinator of the EU-funded Bridge RFID Projects, led the Organizing Committee, together with Duncan McFarlane, Director of the Auto-ID Labs at Cambridge University, who also served as Programme Committee Chair with Dimitris Kiritsis of the EPFL.[8] At this event a representative of the European Telecommunications Standards Institute's Task Group 34 (ETSI TG34) presented the latest regulatory amendments to open additional channels for the use of ISO 18000-6c RFID devices in Europe. Robert Cresanti, Under Secretary of Commerce for Technology and Chief Privacy Officer, United States Department of Commerce, presented the US administration's support for industry-led interoperability initiatives subject to establishing security and privacy for consumers.

Following on the events described above and the collaboration of companies, industry groups, government agencies, and standards bodies, recent progress has occurred in defining specifications for RFID interoperability, most notably in the incorporation of EPCglobal GenII specifications for passive UHF RFID systems into ISO 18000-6c. China's State Radio Regulation Committee (SRRC) has conditionally approved the use of the 920.5–924.5 MHz and 840.5–844.5 MHz UHF spectrum for RFID systems [14]. Concurrently, at the US–European Commission Summit, President Bush and Chancellor Merkel announced an agreement to harmonize technology standards and best practices for RFID [15].

1.4 EPC information services

While RF frequencies and telemetry capabilities extend beyond the EPCglobal Electronic Product Code (EPC) system licensed from MIT, we make a point of considering, in the chapters authored by co-editors John Williams and Sanjay Sarma, the EPC Information Services (EPCIS) specification, released in April of 2007, for describing uniquely identified products in supply chain applications.

[8] The EU RFID Forum 2007 and the RFID Academic Convocation, co-hosted by the Auto-ID Labs at MIT, are being organized around the world to build collaboration across academic disciplines and institutional and geographic boundaries (Brussels, 13–14 March, 2007) (http://europa.eu.int/information_society/newsroom/cf/itemshortdetail.cfm?item_id=3132).

These specifications, developed in the EPCglobal Software Action Group and based on input from hundreds of EPCglobal member companies, represent an opportunity for computer systems to exchange machine-readable data about uniquely identified products, something that is not possible with today's web protocols. The EPCIS interface, for example, could be used for exchanging data independently of specific radio frequencies, transport protocols or even of RFID as a carrier (i.e. EPCIS could be used to exchange 2D barcode or active tag container tracking information). As EPCIS updates are released, the Auto-ID Laboratory at MIT is developing software documentation and data validation tools, together with an open source EPCIS code base, to enable rapid prototyping and testing of EPCIS data exchange over a variety of network bindings and programming paradigms.[9]

1.5 Methodology – closing the loop

Given the multidisciplinary nature of RFID applications and the complexity both of RF performance and of data exchange parameters for RFID-associated data, we propose the use of control theory as an experimental framework for RFID projects, whereby we define a use case, model the system, input data, and analyze the outcome to determine future inputs. This methodology can be used not only for quantifying tag RF power sensitivity (Ch. 3) or the accuracy of various location tracking algorithms (Ch. 5), but also for analyzing communications systems' performance and, at a business process level, measuring the inputs and outputs at various steps in a supply chain control loop. Control theory is at the heart of Six Sigma project management methodology as featured in Sanjay Sarma's work on "Six Sigma Supply Chains" (Ch. 2) that identifies the following processes: Define – Measure – Analyze – Improve – and Control. Control theory is also explored as a modeling framework for EPC network supply chain simulations by John Williams (Ch. 7).

An introduction to RF control systems modeling can be found in MIT OpenCourseware 6.661 taught by David H. Staelin, Ph.D., *Receivers, Antennas, and Signals* [16], that proposes a generic model for communications and sensing systems and also illustrates how passive RF sensing systems differ from active sensing and communications systems.

From Fig. 1.1 we can see how to (A) generate signals, which are processed (B), and then coupled to an electromagnetic environment (D) by a transducer or antenna (C). Another transducer (E) receives those electromagnetic signals and converts them into voltages and currents. In the case of passive RF systems, the transponder (tag) reflects information to the interrogator (reader). One challenge of passive RFID systems that is apparent from this diagram is that, on extending the range of the network to autonomous objects that are not connected to a

[9] The goal of EPCIS is to enable disparate applications to leverage electronic product code (EPC) data via EPC-related data sharing, both within and across enterprises; software tools are available at http://epcis.mit.edu/.

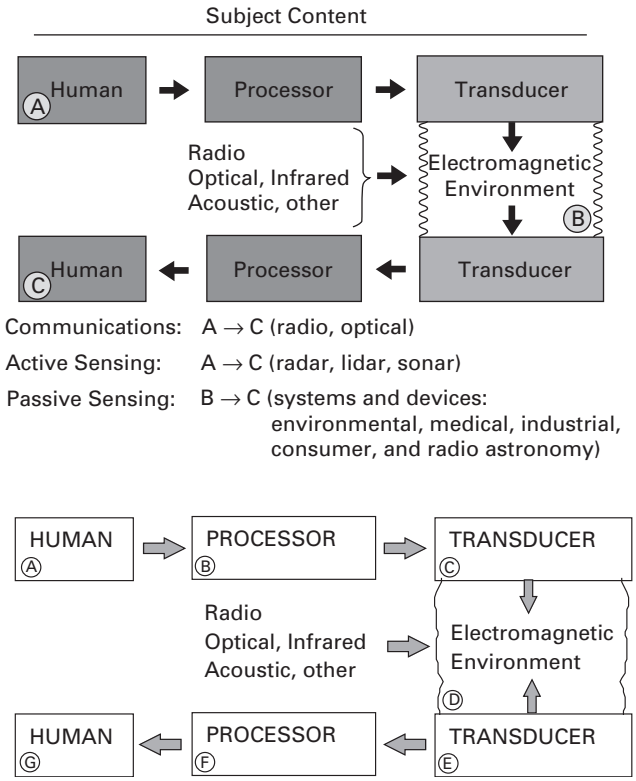

Fig. 1.1 Receivers, antennas, and signals (by David H. Staelin, from MIT OpenCourseware 6.661, 2007, with permission).

network, the information about those objects Ⓔ is not directly connected to an originator "active" or "human" communicator Ⓐ, say, for example, like in the case of a telephone conversation or a client/server or peer-to-peer data exchange. In designing the architecture for an "internet of things" as is addressed in John Williams' "EPC Network Simulation" (Ch. 7), reconstructing the business and security context for "open loop" communications that register isolated EPC events and create business events from them, using a specification such as EPCIS, remains a challenging research area. The chapters that follow can be viewed as control loop experiments for evaluating the use of different technologies, whereby a system is modeled, and events are recorded and analyzed with respect to some metric for measuring outcomes that in turn provides feedback for planning future projects.

1.6 RFID investing in a better future

Changes in regulatory and standards frameworks for RFID across many different countries make this a seminal moment to evaluate RFID technology and