Faranak Nekoogar · Farid Dowla

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To my son, Connor, for his patience throughout preparation of this book.

Faranak Nekoogar

To my son, Maxime, for his "Ultra-wideband" imagination, and my daughter, Emma, for her "Remote Powering" energy!

Farid Dowla

Preface

Long-range radio-frequency (RF) tags are becoming increasingly important in a number of different sensor network applications. Our effort in this book is to discuss the potential advantages of ultra-wideband (UWB) RF systems for designing long-range RF tags that are passive; i.e. *sensors that communicate without batteries*. While the technology of UWB RF tags is still at an early stage of research and development, today UWB communications and radar systems can be considered mature technologies. The GHz's of bandwidth of pulsed RF UWB communications and radar systems have proven to be extremely useful in harsh electromagnetic (EM) environments. Because RF tags address similar technical challenges faced by wireless communication and radar systems, in this book we discuss the key technical challenges of short and long range passive RF tags and discuss how UWB signals and systems might be employed to address those challenges.

When we began the project of writing a book on this subject, our goal was to focus just on UWB RF tags as that was the area of our research and there was a gap on this subject in the technical literature. However, during the process of writing the book, it became clear that the reader would benefit tremendously by including a comparative discussion on narrow-band and low-frequency RF tags in order to evaluate the benefits of UWB RF tags. The first few chapters have been developed to not only review the history and technology of RF tags and RFIDS, but also to discuss the physics of narrowband signaling for RFID's, their advantages and limitations. The later chapters of this book are more focused on discussing the unique features of UWB design that might lead to important insights and breakthrough in future UWB RF tags, and their use in important applications. In our discussion, throughout the book, we have attempted to be up to date and concise, but with extensive references and bibliographies.

The subject of RFID has an audience with a diverse technical background. We have attempted to maintain the contents at an introductory level, while pointing out some of the key reference books and journal papers, for those readers wanting a more rigorous discussion on a subject. We expect this book would be most useful to those wanting a concise overview of the subject. In particular, technical managers responsible to making decisions on the potential use of RFID's for special application areas, might be the ideal audience for this book.

Faranak Nekoogar
Farid Dowla

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Faranak Nekoogar

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List of Acronyms

2D	Two-dimensional
3D	Three-dimensional
ADC	Analog to digital converter
CEPT	Conference european posts and telecommunications
CMF	Classical matched filter
CMOS	Complementary metal oxide semiconductor
COTS	Commercially off the shelf
CW	Continuous waveform
dB	Decibel
dBm	Decibel in milliWatts
DH-TR	Delay hopped transmitted reference
EIRP	Equivalent isotropic radiated power
EM	Electromagnetic field
EPC	Electronic product code
EPROM	Erasable programmable memory
ET	Equivalent time sampling
ETSI	European telecommunications standards institute
FCC	Federal communications commission
FFT	Fast fourier transforms
GHz	Giga Hertz
GPR	Ground penetrating radar
GPS	Global positioning system
HF	High frequency
IF	Intermediate frequency
IFF	Identification, friend or foe
ISM	Industrial, scientific, and medical

KHz	Kilo Hertz
LF	Low frequency
LOS	Line of site
LPI/D	Low probability of interception and detection
LTCC	Low temperature co-fired ceramic
Mbps	Mega bits per second
MHz	Mega hertz
NLOS	Non line of site
OOK	On off keying
PA	Power amplifier
PAM	Pulse amplitude modulation
PEC	Perfect electric conductor
PPM	Pulse position modulation
PRI	Pulse repetition interval
PSD	Power spectral density
Radar	Radio detection and ranging
RCS	Radar cross section
RF	Radio frequency
RFID	Radio frequency identification
ROM	Read only memory
RPMB	Remote-powering modulated-backscattering
SNR	Signal to noise ratio
SRD	Step recovery diodes
TH-PPM	Pulse position modulation with time hopping
TR	Transmitted reference
UHF	Ultra-high frequency
UWB	Ultra-wideband
VHF	Very high frequency
WBAN	Wireless body area network
WORM	Write once, read many
WLAN	Wireless local area network

Chapter 1
Basics of Radio Frequency Identification (RFID) Systems

1.1 Introduction

With the recent advances in wireless communications, Radio frequency Identification (RFID) technology is becoming more of a reality in terms of their widespread use in various applications. Although RFID provides a general capability for tagging and tracking of objects, and has been in use for decades, no RFID system fits all applications. Therefore, it's important to start this introductory chapter with an overview of the technology in general terms and continue in the later chapters with more detailed discussions on various techniques that can make RFIDs more adaptable to some specialized applications that face challenges with conventional RFID techniques.

This chapter provides a general introduction to RFID systems and serves as a prerequisite to the following chapters, in which challenges of conventional RFID systems are discussed and ultra-wideband RFID solutions are introduced. In this chapter, we start with a brief overview of RFID technology and include a detailed discussion on the history of RFIDs and their evolution from the early 1800s to present. Next we cover RFID frequency bands and discuss their advantages and challenges for a variety of applications. The chapter then continues with a detailed discussion of RFID components including tags, readers, middleware and application software. The subsections of this chapter provide a comprehensive overview of different types of RF tags and their memory components, inductive and magnetically coupled readers with their advantages and limitations under various conditions and applications. We end the chapter with a concise overview of RFID applications and their important parameters categorized by different market sectors.

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1.2 RFID Background

Radio Frequency IDentification (RFID) is an enabling technology for remotely identifying, monitoring, and tracking various objects of interest using radio wave transmissions. The automatic identification of objects is possible by wireless communications between a tag (attached to an object) and its reader (interrogator) at a distant location. RFID remote monitoring can range from detecting the presence and absence of an object to tracking its movement over short or long distances. A typical RFID system is comprised of the following components:

- One or more tags or transponders with unique identification codes and a small antenna embedded within each tag.
- A reader, or interrogator, with one or more antennas that are connected to a host computer through various kinds of interfaces such as: USB, PCMCIA, RS232, or wireless interfaces such as Bluetooth.
- Application software or middleware running on a host computer to translate the received data to user-friendly messages regarding the tagged item's presence and absence status or its location.

Figure 1.1 represents a typical RFID system and its components.

RFID is a fast and reliable technology that does not require physical contact or line-of-sight (LOS) link between the tagged items and the readers, hence it reduces the human intervention for real time tracking and monitoring of assets. In many documents, RFID is considered as a future replacement of barcodes and is referred to "a barcode that barks".[1] Although RFID tags are more expensive than barcodes, there are certain advantages that make RFID more attractive than barcodes for a variety of applications. Table 1.1 summarizes a comparative analysis of RFID tags versus barcodes with an advantage arrow pointing to each technology in different cases.

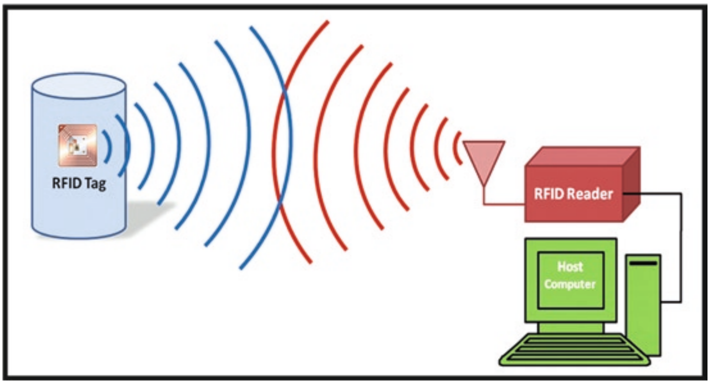

Fig. 1.1 Components of a typical RFID system

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[1] http://www.stormfront.org/forum/showthread.php?t=170821&page=3.

Table 1.1 A comparative analysis of RFID tags versus barcodes

	RFID Tags	Advantage	Barcodes
Method of data transfer	Radio frequency link		Optical link
Number of years in use	First used in WWII (1942) for distinguishing between friendly and enemy airplanes.	⇦	First commercial use in 1974 at Marsh supermarket in Troy, Ohio (first product scanned: Wrigley's chewing gum) [1].
Automation	Totally automated system once installed.	⇦	Fully dependent on human operator to scan the items one by one.
Line-of-Sight requirement	Items can be detected in any orientation within the read range.	⇦	Specific orientation is needed for reading the labels.
Read/Write capability	Information can be dynamically written and updated on a tag.	⇦	Read only without any upgrade capability.
Multi-item detection (read rate) capability	Thousands of tags can be detected simultaneously.	⇦	Labels have to be read one at a time.
Performance around metals	Typically difficult (currently). Metallic background degrades the read performance.	⇨	No degradation due to metallic background.
Robustness	Relatively high. Tags can be internally attached and protected from removal.	⇦	Easy to remove or impair. External dirt or grease can obstruct the signal.
Security	Tags can be designed with encryption, authentication, and tamper indication capabilities	⇦	Easy to counterfeit.
Event notification	Tags can be integrated with various sensors and report various events such as temperature, pressure, etc..	⇦	Not capable of notifying any events.
Remote monitoring capability	The presence or absence, and in some cases the possible location of items can be detected from a distance (range dependent).	⇦	Needs close, line of sight contact to scan the item.
Mobility (read while an object is moving)	RF tags provide real-time monitoring regardless of movement.	⇦	Needs to be stationary at line of sight of the scanner.
Positioning capability	Some RFID tags provide the location information of an item.	⇦	Does not provide location capability. Not useful for remote monitoring.
Cost	Higher cost (depending on the tag capabilities)	⇨	Very low.

As illustrated by Table 1.1 RFID promotes many advantages over a conventional bar code. The comparison between the two models reveals a distinct advantage of RFIDs over barcodes in remote-monitoring applications. Furthermore, RFID, as a technology houses more capabilities, features, and functions than a barcode at a higher cost.

1.3 Evolution of RFID Systems

Despite the common misconception, RFID is not a new technology. Identifying objects by means of reflected radio waves was heavily used by Europeans in World War II (1940’s) to detect friendly aircrafts from enemy planes entering their skies. German pilots maneuvered their planes to generate a unique reflected signal for ground radars in order to be differentiated from enemy planes. This essentially accounts for the first passive RF Identification system. Soon after that, the British refined the idea and developed the active IFF (Identification, Friend or Foe) system where a transponder (size of a suitcase) was attached to the fuselage of an aircraft and transmitted RF signals with a unique signature to communicate with its base as a friendly aircraft returning from a mission [2].

A decade later in 1948, the first idea behind RFID was published by Harry Stockman, in a paper titled “Communication by Means of Reflected Power” [3]. However, the true ancestor of RFID systems is known as the first active RFID invention recorded by Mario Cardullo in 1969 [4, 5]. In his patent, Cardullo refers to an active identification tag with rewritable memory using either RF, acoustic, or light signals. This invention was followed by the invention of the first passive RFID system in 1973 by Charles Walton of Proximity Devices in Sunnyvale, CA [6] for the first keyless entry system using a card with an embedded transponder to communicate with a reader attached to a door. In 1975 a great deal of research, development, and demonstration of passive and semi-passive RFID systems was reported by Los Alamos National Laboratory scientists under funding from Department of Energy (DOE) [7, 8].

Despite all the efforts in research and development of RFIDs in early years, the use of this technology only became possible in 1990s when the advancements in materials and semiconductor technology offered improved performance in semiconductor chips while reducing their size and cost. This breakthrough enabled commercial RFID systems to enter the mainstream and be widely used in a variety of applications including security and access control, transportation, toll systems, and supply chain management and tracking.

It is important to note that prior to 1990s, the RFID systems were all proprietary solutions for various applications when there were no standards defined for interoperability between RFID systems, which posed an obstacle for growth of this technology. The 1990–2000 time period was considered the decade for emergence of RFID standards; where several organizations such as the International Standards

Table 1.2 Historical timetable of technologies and efforts related to RFID development

1800–1900	Faraday, Maxwell, Hertz early discoveries of electromagnetic energy and waves
1901	Marconi demonstrated the first UWB radio transmission over Atlantic ocean
1925	Birth of Radar
1939	First RFID concept for IFF systems in WWII
1948	First technical idea behind RFID was published by Harry Stockman
1969	Mario Cardullo invented the first active RFID system
1973	Charles Walton invented the first passive RFID system
1975	Extensive research and development of passive/semi-passive RFIDs in Los Alamos National Laboratory
1980–1990	Implementation of proprietary RFID systems
1990–2000	RFID technology enters the mainstream, emergence of RFID standards
2002	FCC approved UWB technology for commercial applications
2003	EPC technology adopted by Walmart and DoD, first UWB RFID developed by MSSI
2003–Present	Years of technical advancements in overcoming RFID practical challenges

Organization (ISO) and the European Conference of Postal and Telecommunications Administrations (CEPT) proposed regulations for RFID interoperability and frequency allocation. The Auto-ID center at MIT was founded in 1999 to establish an open standard for RFID networking and interoperability. In 2003, Auto-ID center merged by EPCglobal which was a joint venture between EAN International and the Uniform Code Council to commercialize EPC (Electronic Product Code) technology.

The year 2003 was also an exciting year for RFID technology since both Wal-Mart and the U.S. Department of Defense (DoD) adopted EPC technology for supply chain management. Furthermore, after FCC approval of Ultra-wideband (UWB) technology for commercial use in 2002, the commercial UWB RFID systems were introduced by companies such as MultiSpectral Solutions (MSSI) Inc., Time domain Inc., and Ubisense Ltd. These advanced RFID systems offered a breakthrough in tagging and tracking technology with improved range and functionality. However, to the date of writing this manuscript, some of the unsolved technical challenges that RFIDs' face, in addition to the high cost of tags, have been a barrier for widespread use of them in many practical applications.

The Table 1.2 summarizes the historical timeline starting from scientific advancements in electromagnetic energy and wave propagation to RFID development and standardization efforts (Table 1.2).

1.4 RFID Frequency Bands

The operating frequency of an RFID system directly influences its read range and therefore its target application. Table 1.3 shows the four main spectral bands allocated for COTS RFID systems.

Table 1.3 Frequency bands used for RFID systems

Low frequency (LF)	High frequency (HF)	Ultra high frequency (UHF)	Microwave Frequency
125–134 KHz	13.56 MHz	868–928 MHz	2.4 GHz

1.4.1 Low Frequency (LF) Band

This frequency band covers the RF spectrum from 125–134 KHz and provides good signal penetration through a range of materials including human body or various walls and barriers. The RFID tags operating in these low frequencies have the advantage of performing well around a variety of conductive and dielectric materials such as metal, soil, and water. Therefore, LF tags are good candidates for personnel and animal tracking as well as in the automotive industry.

The LF RFID systems are less susceptible to external interference since the lower frequency bands are less crowded with radio services. Another argument to support the relatively low sensitivity of RF tags to interference at low frequencies is that such frequencies mostly include narrowband systems[2] and the noise level seen at the input of their receivers is low according to the basic theory for the ambient thermal noise shown in the following equation.

$$N_0 = KTB \tag{1.1}$$

Where N_0 is the ambient thermal noise seen at a receiver input, K represents the Boltzmann's constant equal to $1.38 \times 10^{-23} (J /^{\circ} K / Hz)$, T is the ambient temperature equal to $293(^{\circ} K)$, and B is the signal bandwidth. Therefore, we see from (1.1) that the smaller the bandwidth (resulting from low frequencies) the lower the receiver noise level.

The range expected from tags operating at low frequencies is from few centimeters to few meters depending on the size of the antennas and the sensitivity of their readers. However, the lower the frequency, the larger the antenna size which causes a physical limitation for most tags in terms of size and hence the range remains in the lower limit of few centimeters for most applications. It's important to mention that due to the antenna size limitation of RF tags for low frequencies, these tags are mainly inductively coupled, therefore their read ranges drop very fast with distance, by a factor of $\frac{1}{r^3}$ where r is the distance between a tag and its reader.[3]

Finally, there are additional limitations to the capability of LF RFID systems for many practical applications due to their low data rate (on the order of a few bits/s) and the slow read rate. Furthermore, as one can infer from the general evolution of

---

[2] Low frequency radios are mainly narrowband systems since there is not enough bandwidth available in the spectrum for such radios to be wideband.

[3] The $\frac{1}{r^3}$ factor is a component indicative of the proportion between read range and magnetic field strength; the magnetic field being the medium of choice for typical LF RFIDs.

the technology, modern demand for such communication systems like RFID require the transmission of more information and at faster speeds.

1.4.2 High Frequency (HF) Band

The passive HF RFID systems operate at 13.56 MHz and are used where medium data rate (on the order of Kbps) and short read ranges (<1 m) are sufficient for applications such as smart cards, short range item level tracking such as tracking books in libraries, etc. Their performance in the presence of water and metals are lower compared to LF tags but better than higher frequency tags such as UHF and microwave tags. The HF tags have the capacity for larger memory and faster communication speeds than the LF tags, giving them the ability to detect multiple tags at once. Furthermore, these tags have shorter wavelengths compared to LF tags, therefore, they have smaller and less expensive antennas. Similar to LF tags, the HF tags also use the inductive coupling for communications with their readers.

1.4.3 Ultra High Frequency (UHF) Band

RF tags operating in UHF band (868–928 MHz) use backscatter technology for their tag-reader communications where the tag reflects back the electromagnetic signal it receives from its reader. The UHF tags offer longer ranges (typically 3–10 m range) and higher reading speeds, support simultaneous detection of more number of tags compared to LF and HF systems, and finally need smaller antennas. However, the read range of these significantly deteriorates[4] around metallic and liquid surfaces and their cost is higher than the LF and HF RFID tags. Furthermore, these tags are not global in the sense that the power level and operating frequency of UHF tags varies in different parts of the world. Table 1.4 represents the power level and frequency of operation in different regions.

As described in Table 1.4, RFID systems in UHF bands have difficulty in worldwide operations. In addition, the operating frequency for these tags falls into the

Table 1.4 UHF frequency bands and their allowed maximum EIRP for few regions of the world

Country	Frequency band	Maximum EIRP (EIRP is the effective isotropic radiated power) allowed
United States	902–928 MHz	4 W
Australia	918–926 MHz	1 W
Japan	950–956 MHz (Experimental purposes only)	4 W
Europe	865–867 MHz	2 W

---

[4] Active research is currently going on for improving the performance of UHF tags on metallic objects.

crowded unlicensed ISM (Industrial, Scientific, Medical) band, making the UHF tags susceptible to all kinds of electromagnetic interfering signals. The UHF tags are usually used in supply chain and asset management applications.

1.4.4 Microwave (MW) Band

The microwave band (2.4 GHz), *offers* high data transfer rates (Kbps) and long distances (~30 m) and is typically used in toll collection applications. RFID systems at this frequency band are expensive and require line of sight transmission. The reason is that in such high frequencies non-line-of-sight (NLOS) signals suffer more significantly from propagation effects such as multipath interference and signal diffraction. In addition, microwave tags do not penetrate many materials and their read performance suffers considerably from being adjacent to metals and water.

As explained earlier in this section, each of the aforementioned frequency bands offers advantages and challenges for the operation of RFID systems. The tags in lower frequency bands such as LF and HF provide better performance near metal and water than the higher frequency ones. However, their data rate is slower and they have shorter read range. The higher frequency bands provide faster speeds and longer read ranges but they suffer from higher attenuation rates, are more expensive, and require more regulatory control.

Table 1.5 summarizes the RFID frequency bands based on their advantages and disadvantages as well as their typical applications.

As we see in Table 1.4 the lower frequencies have better performance around metal and water, while they have lower data rates and lower speed of communications. On the other hand, the higher frequencies have longer range and higher communications speed with poor performance around metallic and liquid objects as summarized in the next Fig. 1.2.

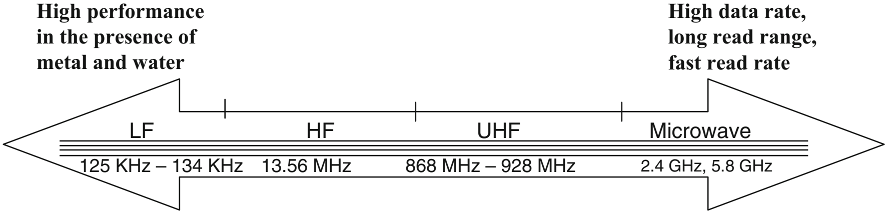

Fig. 1.2 Portions of RF electromagnetic spectrum for conventional RFID systems, and RFID capabilities at each end of the spectrum

Table 1.5 Summary of RFID systems with various operating frequencies

Frequency	Advantage	Disadvantage	Typical application
LF (125–134 KHz)	• Less vulnerability to signal degradation from liquids and metals • High penetration properties • Robust to interference	• Limited range • Low reading speed • Low memory capacity • Large antennas • Slow data transfer • High production cost • Limited read range	• Access control • Animal ID • Automotive
HF (13.56 MHz)	• Lower production cost • Increased data storage capacity		• Short-range item-level inventory management
UHF (868–928 MHz)	• Improved read range	• Restriction of use in different countries • Both tags and readers need to be designed for different parts of the world	• Smart cards • Supply chain management
Microwave (2.4 GHz, 5.8 GHz)	• Longer range	• Vulnerable to interference from unintentional signals in close vicinity • Signal propagation issues (LOS, shadow effect) • Attenuation by water	• Warehouse palette control • Transportation toll control

1.5 Overview of RFID Tags

An RFID tag or transponder is a small device (generally smaller than the size of a credit card) that is comprised of a small antenna attached to a microchip and an integrated circuit (IC) to store the information unique to the object that it's attached to. The tag antenna is a small coil of wires covered with a protective layer and allows the wireless communications between the tag and its reader as shown in Fig. 1.3.

The tag IC provides a range of functionality such as: the basic logic to provide multi-tag detection, storage of data in memory, and the modulation of the data. RFID tags can be embedded onto individual items as wells as pallets and containers filled with many items. From a functional point of view, RFID tags are classified to four major categories: active, semi-active, passive, and semi-passive. We discuss these categories in the following subsections.

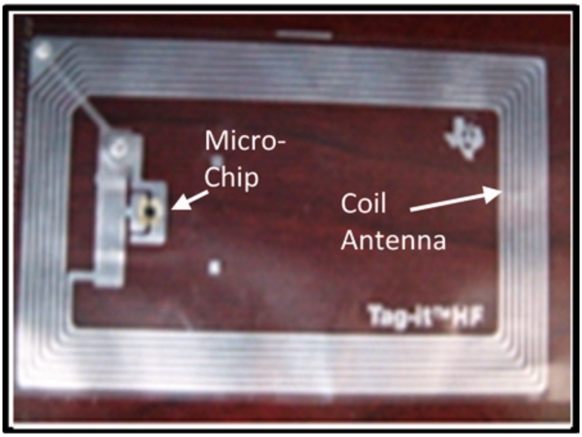

Fig. 1.3 Example of an RFID tag showing the IC and its coil antenna

1.5.1 Active Tags

Active RFID tags require an onboard source of energy (battery) to power their communications. The active RFID communication model is no different than any other wireless communication system where transmitters (tags) communicate with receivers (readers) over a wireless link using radio waves. Hence active tags can initiate communications with their reader to broadcast information and in some cases can also form a peer-to-peer network. Figure 1.4 illustrates an active RFID communications model.

The communication range of active tags is relatively long, about a few hundred feet, therefore they can provide positioning capability to their users for tracking tagged items in addition to detecting their presence or absence. In addition, active tags have valuable features such as a large user-defined memory, and the extensibility to add sensors. However, since active tags need on-board power source and transmit/receive circuitry, they are large in size, heavy, and expensive (on the order of $10–$50 per tag depending on the functionality). Furthermore, their lifetime is limited by their battery life since they continuously consume power whether they

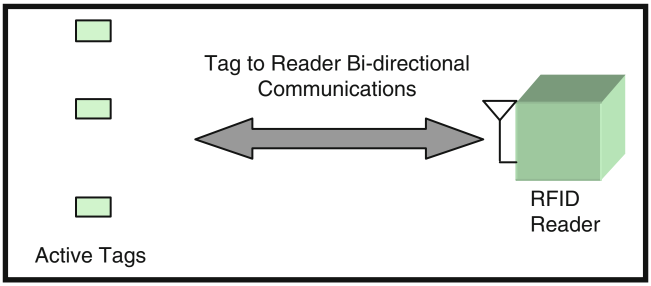

Fig. 1.4 Active RFID communications model; tags transmit the data modulated RF signals to their reader

Fig. 1.5 A typical active tag

are in the presence of a reader or not. Active tags are typically used in tracking high value items for long-range applications such as vehicles and large containers. Figure 1.5 shows samples of typical active tags.

1.5.2 *Semi-active Tags*

Similar to active RFID tags, semi-active ones require an onboard source of energy (battery) to power their communications. The semi-active RFID tags are transceivers that actively transmit RF signals once their battery is activated by an activation signal from their readers. Semi-active tags "CANNOT" initiate communications with their reader and are in sleep mode all the time before their reader wakes them up. Figure 1.6 shows an example of a semi-active RFID communications model.

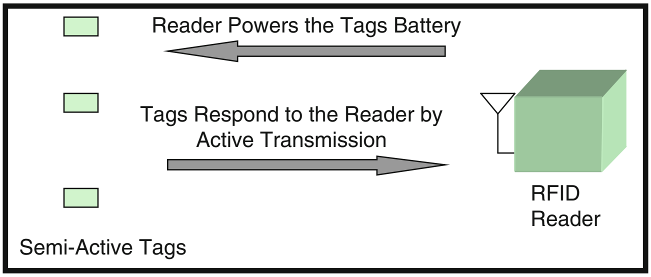

Fig. 1.6 Semi-active RFID communications model; reader wakes up the tags and tags transmit the data modulated RF signals to their reader

Semi-active tags have the advantage of long range communications and large user accessible memory, similar to active tags, while their battery lasts longer than active tags. Many commercial products may not distinguish the difference between the concept of active and semi-active RFID and may use the semi-active model as a form of power management for active tags. However, from a conceptual point of view, it's worth understanding the differences.

1.5.3 Passive Tags

Passive RFID tags have no onboard source of power such as a battery; instead these tags obtain their operational power from harvesting the electromagnetic energy emitted from their reader in close vicinity. This remote powering scheme, as we will further investigate in more detail, is commonly known as electromagnetic induction technique. The tags temporarily store a small amount of energy emitted from the reader, convert it to DC power in order to power up their microchips and generate their response. Therefore, the antenna of a passive tag needs to be designed to perform two tasks; (1) collecting power from its reader (2) and to reflect or backscatter the outgoing signal. Figure 1.7 illustrates a passive RFID communications model.

Passive tags can be manufactured in very small form factors, and are lighter and less expensive compared to active and semi-active tags. However, their communications range is shorter than battery operated tags. Also, they need high power readers to power them up considering the previously noted $\frac{1}{r^3}$ limitation. Passive tags are usually used for tracking high quantities of lower cost items in short ranges (Fig. 1.8).

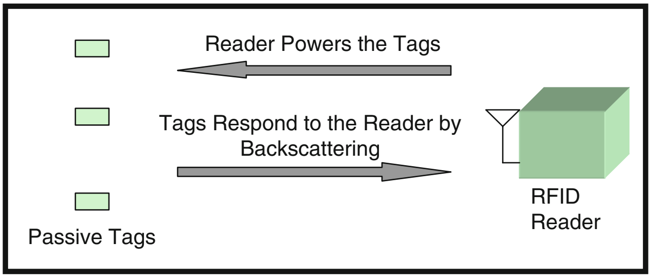

Fig. 1.7 Passive RFID communications model; tags obtain their operational power from their reader; then they reflect/backscatter the data modulated RF signals to the reader

Fig. 1.8 Example of passive tags (courtesy of Texas Instruments, reprinted with permission)

1.5.4 *Semi-passive Tags*

Semi-passive or battery assisted passive (BAP) RFID tags include a power source that is only activated when tags are "awakened" by their reader. Therefore, their battery lasts longer than active tags and their read range is longer than passive tags. The battery source on semi-passive tags is only used to provide power to the tag circuitry, however these tags do not actively transmit RF signals and cannot initiate the tag-reader communications. The tag-reader communications in semi-passive systems is based on backscattering method (just like passive tags). Figure 1.9 illustrates a semi-passive RFID communications model.

Again, since these tags contain a battery source, they are lager in size and are more expensive than their passive counterparts, but they certainly fill the gap between the short range passive and expensive active tags (Fig. 1.10).

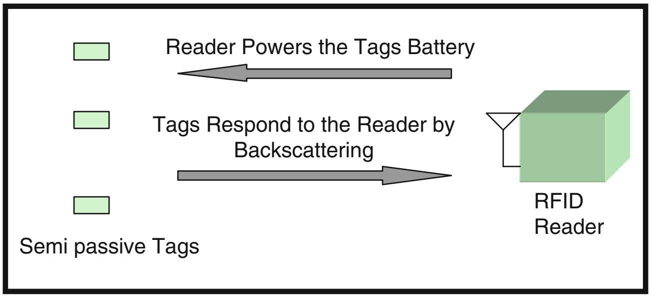

Fig. 1.9 Semi-passive RFID communications model; tags transmit the data modulated RF signals to their reader

Fig. 1.10 Example of semi-passive tags

Table 1.6 provides an overview of the technical differences and functional capabilities of active, semi-active, semi-passive, and passive RFID systems.

1.5.5 Memory Components of RF Tags

Besides the antenna and powering circuitry, RFID tags have a memory component in their chipset to store unique information. Depending on their applications, the memory capabilities of tags can vary as:

- Read-Only
- Write Once Read Many (WORM)
- Read/Write

Read-Only tags are programmed with unique identification that is stored on them during the manufacturing process. These tags are not rewriteable and their information can never be changed. Although read-only tags have limitation for certain applications, they are inherently secure with respect to vulnerabilities such as counterfeiting, spoofing, or cloning.

Read/Write tags are capable of being written and read several times to update their database. The user can add additional information or overwrite the existing information for specific applications. Due to its sophistication in terms of configuring stored information, these tags are significantly more expensive than read only tags.

Write-Once-Read-Many (WORM) tags can be written only once to add more information beyond their unique identifier and they become read-only tags after the first write. WORM tags provide a higher level of security compared to read/write tags where they could be changed at anytime outside the control of the manufacturer.

1.5.6 Classification of RFID Tags by EPCglobal

RFID tags are classified by EPCglobal into six different layered class structures (class 0–class 5) based on their level of complexity and functionality.

Class 0 tags are the most basic and least sophisticated RFID tags with passive read only functionality where the tags are programmed at the time of the manufacturing

Table 1.6 Technical summary of the major RF tag categories

	Active	Semi-active	Semi-passive	Passive
Tag battery required	Yes	Yes	Yes	No
Tag power source and availability	Internal battery, continuously available	Internal battery, available only after a wake up signal from the reader	Internal battery, available only after a wake up signal from the reader	Obtain RF energy generated from the reader, only when tag is in the reader's vicinity
Tag-reader communications	Active transmission	Active transmission	Backscatter	Backscatter
Reader-to-tag signal strength (range dependant)	Low	Low	Low	High
Tag-to-reader signal strength (range dependant)	High	High	High	Low
Communication range	Long > 100 m	Long > 100 m	Long > 100 m	Short < 10 m
Data storage capacity	Large	Large	Large	Small
Read/write capability	Yes	Yes	Yes	Read only
Cost	Expensive	Expensive	Less expensive	Least expensive
Typical application	Large asset tracking	Large asset tracking	Electronic toll	Proximity cards

Table 1.7 Summary of EPCglobal classification of RFID tags

EPCglobal Tag Class	Functionality
Class 0	Passive, read only ID tags, factory programmed, backscatter communications
Class 1	Same as Class 0 with write once capability
Class 2	Passive tags, read/write, extended memory, encryption, backscatter communications
Class 3	Semi-passive, battery assisted passive, longer range, backscatter communications
Class 4	Active tags, battery operated, active transmission, peer-to-peer network
Class 5	Same as Class 4 tags with the ability to power up passive tags

of their microchips. These tags are simple identity tags and use backscattering technology for their tag-to-reader communications (reverse link).

Class 1 tags are similar to Class 0 as being passive and read only ID tags, with the difference that class 1tags can be written once by their users. These tags also use backscattering technique for tag-reader communications.

Class 2 tags are considered as higher functionality passive tags with extended memory and read/write as well as authentication and encryption capabilities.

Class 3 tags are semi-passive or battery assisted passive tags at UHF frequencies that have a power source to operate their internal circuitry while still responding passively by backscatter at reverse link.

Class 4 tags are active tags with internal power source (battery) and RF transceivers to receive and transmit signals. These tags are more complex and have advanced functionality with higher communication range. Class 4 tags can also communicate with each other and form a peer-to-peer network.

Class 5 tags are active tags like the Class 4 tags, however, they have the additional capability of powering up passive tags also. Table 1.7 summarizes the tag classification by EPCglobal standards.

1.6 Overview of RFID Readers

A typical RFID reader or interrogator is a specialized radio whose antenna collects the signals sent by active and semi-active tags or reflected (backscattered) signals from passive and semi-passive tags. In other words, the reader acts as a bridge between the application software and the tags that transfer the information. RFID readers can have multiple antennas to achieve greater operating range or area of coverage. Readers can be placed in a fixed position such as in portal applications, or be portable hand-held for many scanning applications. Figure 1.11 shows an example of a commercially available RFID reader.

In active and semi-active RFID systems, the reader is a specialized receiver that detects the received signals actively being sent by tag transmitters. However, in passive RFID systems, the reader not only listens for the signals reflected from the tags, it also transmits the RF signal that powers up the tags. The semi-active and semi-passive RFID readers send a signal to activate the battery in the tags, and detect the

Fig. 1.11 Example of an RFID reader

actively transmitted signal from the semi-active tags and the backscattered signals from the semi-passive tags.

Passive RFID readers power up their tags with two major EM coupling methods:

- Magnetic Field Coupling
- Electric Field Coupling

Each of these coupling methods has an influence over the communications range of RFID systems and is described in more detail in the next subsections.

1.6.1 Magnetic Coupling: Near Field

In nearfield or magnetic coupling the tag antenna is inductively coupled with the strong electromagnetic (EM) field around the reader's antenna coil. This is the same principle used in transformers where from Faraday's law the reader's alternating magnetic field (primary coil) generates a voltage in the tag's antenna (secondary coil) [9]. Nearfield coupling occurs mostly in LF and HF RFID systems where the distance between the tag and the reader antenna is much smaller than their wavelength (i.e. 13.56 MHz has a 22.1 m wavelength[5]). Therefore, this type of coupling provides very limited read ranges for RFID systems.[6] Figure 1.12 illustrates the concept of tag powering using magnetic coupling.

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[5] Wavelength for a typical HF RFID tag is calculated as: $\lambda = \frac{C}{f} = \frac{3\times10^8}{13.56\times10^6} = 22.1\ \text{m}$

[6] Magnetic field decreases by a factor of $\frac{1}{r^3}$ in free space, where r is distance between the tag and reader antenna.

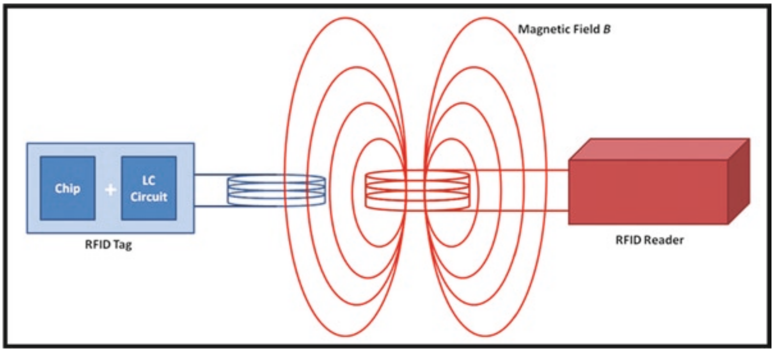

Fig. 1.12 Magnetic (nearfield) coupling to power up a transponder

The magnetically coupled tags have an antenna with a multi-turn coil where each coil is an LC circuit tuned to the desired frequency (i.e. 13.56 MHz) to maximize the energy collection from the readers by alternating magnetic field. The number of turns in HF tag antenna coils is less than the number of turns in antennas for LF tags. In this type of coupling, tag-reader communications is based on modulating the digital data by alternating the strength of the magnetic field that in practice provides AM modulation for the digital data to be transmitted. Magnetically coupled tags have very limited energy storage capacity; hence the magnetic field has to be applied constantly during tag interrogation.

1.6.2 Electric Coupling: Far Field

Electric or capacitive coupling is used in higher frequency (UHF and microwave) tags and provides a much longer communications range for RFID systems compared to magnetic coupling technique.[7] The energy transfer in this coupling method is achieved in farfield, where the electric and magnetic field components of an antenna propagate into free space as a combined electromagnetic wave. It's important to note that in the far field, inductive coupling is no longer possible since the magnetic field is not linked to the antenna any longer [9].

Electric field coupling uses the same principle as radar where the transponder is powered up by the strong electrical field generated by its reader and reflects (backscatters) the received signal. Figure 1.13 represents the electric coupling of a tag by its compatible reader.

In electric coupling, tag-reader communications occurs by variations in the load impedance of the tag antenna resulting in a unique backscattered signal that can be decoded by the reader. In this modulation technique, the tag is intentionally mistuned to its antenna's frequency to reflect the received signal instead of absorbing it.

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[7] Electromagnetic field decrease by a factor of $\frac{1}{r}$, where r is distance between the tag and reader antenna.

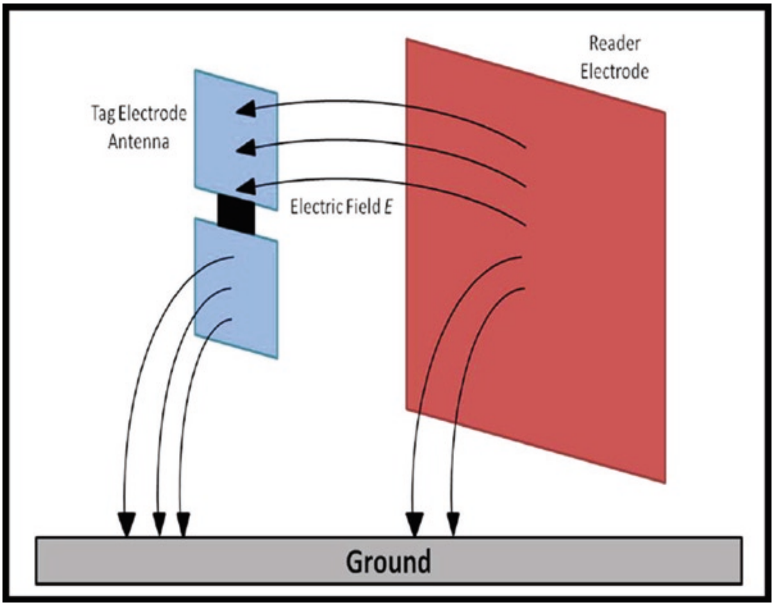

Fig. 1.13 Electrically coupled RFID systems

1.7 Middleware and Applications Software

RFID middleware is a specialized software platform that plays a crucial role of controlling the data flow between RFID readers and the application software. The middleware is basically called the brain of the RFID system and performs many complex operations including:

- Collecting and accumulating raw data from tags
- Preventing redundancy by filtering reader's digital data
- Local processing of raw data from readers
- Managing reader configurations
- Managing the false tag reads
- Read/write operations

In addition, middleware contains a backend database system (i.e. Oracle, MySQL, etc.) for sorting and quarrying the tag information [10].

The application software translates the digital bits provided by the middleware to business specific and user-friendly messages including the presence or absence of a specific item as well as its location for inventory purposes. Figure 1.14 summarizes the role of the middleware in a RFID system.

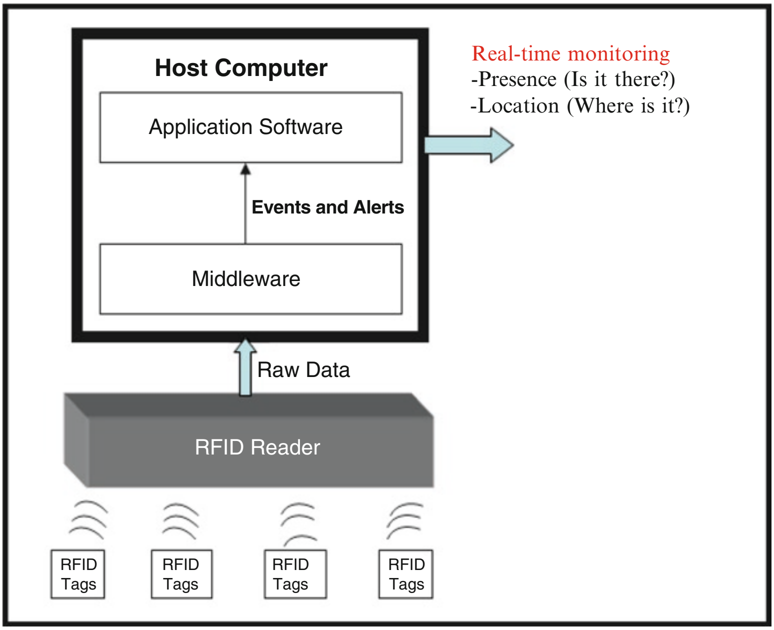

Fig. 1.14 Middleware provides connectivity between the readers and the application software

1.8 RFID Applications

RFID is a versatile technology that has a place in many applications. The ability to tag and track assets with a unique identity can create the future concept of “The Internet of Things” [11–13] which will have a great impact in our everyday lives.

Although RFID solutions are already playing an essential role in many commercial and military applications, the technology still needs to evolve extensively for its widespread use. Certain parameters such as cost as well as technical issues including power consumption, read range, performance around liquids and metals are still limiting factors for RFID deployment to its full extent. Table 1.8, represents a limited list of RFID applications and important parameters in the market place.

1.9 Summary

With the recent advances in materials and semiconductor device technology, RFID systems have become more mature and cost effective to improve the business efficiency in many applications. In this introductory chapter, we discussed a brief history and background as well as the basic concept of RFID systems. The chapter also covered RFID components including tag types, classification of tags based on

Table 1.8 Limited list of RFID market sectors and their important parameters

Application	Examples	Presence/ Absence	Positioning	Tamper indication	Cluttered (metallic) environment
Animal management	Livestock tracking, wildlife monitoring	√	√	X	X
Health care	Patient monitoring, drug counterfeiting, tracking surgical equipments	√	√	X	√
Construction	On-site personnel and asset tracking	√	√	X	X
Shipping	Package tracking, cargo containers	√	√	√	√
Retail	Inventories, warehouse management	√	√	X	√
Airports	Baggage tracking	√	√	√	X
Transportation	Automated toll collection, vehicle identification in parking lots	√	√	X	√
Industrial manufacturing	Part tracking	√	√	X	√
Security	Access control, keyless entry, anti-theft systems	√	√	X	X
Homeland security	Border crossing	√	√	X	X

EPCglobal standards, tag memory, reader types, middleware and application software as a general overview to RFID technology. Furthermore, the applications of RFID for various commercial markets were explained briefly. This chapter is meant to serve as background information and a prerequisite for more advanced topics discussed in the later chapters including: understanding the characteristics and limitations of narrowband signaling for RFID systems, ultra-wideband (UWB) signaling for RFID systems, UWB signals and systems for RFID applications, UWB RFID antennas, as well as UWB RFID for special applications.

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Chapter 2
Characteristics and Limitations of Conventional RFIDs

2.1 Introduction

Although RFID technology has been proven to be sufficiently adequate for some applications, such as toll collection and anti-theft systems, there are numerous other applications that cannot benefit from this technology due to some of the limitations of the conventional RFID technologies. With the widespread interest and usage of RFIDs, the vulnerabilities of current RFID systems are becoming apparent. These limitations are directly related to the environment that the tags and readers communicate. This environment consists of both the wireless channel and the physical object that the tags are attached to. Various objects and systems in the wireless channel can cause a range of signal degradation such as attenuation, multipath fading, and interference to the RF signal carrying the tag information. Since the reliability of an RFID system is directly dependent on the robustness of the tag-reader RF link, the signaling scheme becomes a fundamental area of study for characterization and further performance improvement of such systems.

To date, most of the commercial RFID systems use narrowband signaling (continuous sinusoidal waveforms) for their tag-reader RF link, therefore they face the same difficulties that any narrowband wireless communications system may encounter. In this chapter we start with a general overview of the issues associated with narrowband signaling in RFID systems. Then we provide a comprehensive performance analysis of some of the commercial UHF RFID systems to characterize their performance and report on their capabilities and limitations for various applications.

The chapter ends with a brief discussion on ultra-wideband technology and how it can address many of the challenges associated with existing RFID systems. This discussion sets the ground for Chaps. 3, 4, 5, and 6 that offer an extensive discussion on use of UWB technology in RFIDs with detailed overview of implementation aspects of UWB pulses, discussion on UWB antennas for RFID tags and readers, and overview of special applications that could benefit from UWB RFIDs.

F. Nekoogar and F. Dowla, *Ultra-Wideband Radio Frequency Identification Systems*,
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2.2 Physics of Narrowband Signaling

RFID systems that use narrowband signaling for tag-reader communications face certain technical challenges related to the physical properties and propagation characteristics of narrowband RF signals. Figure 2.1 represents a narrowband signal in time and frequency domain.

As shown in Fig. 2.1, a narrowband signal uses a specific carrier frequency and has well-defined signal energy in a very narrow frequency band [1]. The nature of continuous waveforms (CW) and their high power spectral density in a very narrow frequency band, limits the suitability of narrowband signals in many RFID applications. These limitations include susceptibility to detection and tampering, poor performance around metallic objects, signal blockage, privacy issues, inadequate range of passive tags, high power consumption of active tags, and limitations to worldwide operations. The above-mentioned limitations and challenges are discussed in great detail in the following subsections.

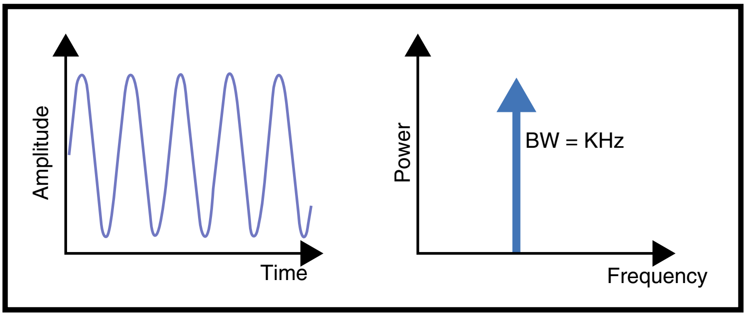

Fig. 2.1 A narrowband signal in time domain (*left*) and frequency domain (*right*)

2.2.1 *Performance Limitations Around Metallic Surfaces*

One of the major challenges that RFID systems with narrowband signaling face is the poor performance around EM reflective objects and materials. This is due to multipath phenomenon caused by reflection of continuous RF waveforms from metallic surfaces that can destructively add and degrade the received signal. Figure 2.2 represents multipath phenomenon in narrowband signaling.

Although multipath effects can also degrade the performance of active tags, their effect on passive tags can be more dramatic. Since passive RFID tags have to extract power from their reader's transmitted signal, if the energy transfer is not efficient due to antenna impedance mismatch near conductors, such as a metal surface, the tag will not power up and will fail to operate. Because antenna efficiency is a function of frequency, the lack of frequency diversity can result in significant performance degradation of tags that are attached to metal surfaces. Figure 2.3

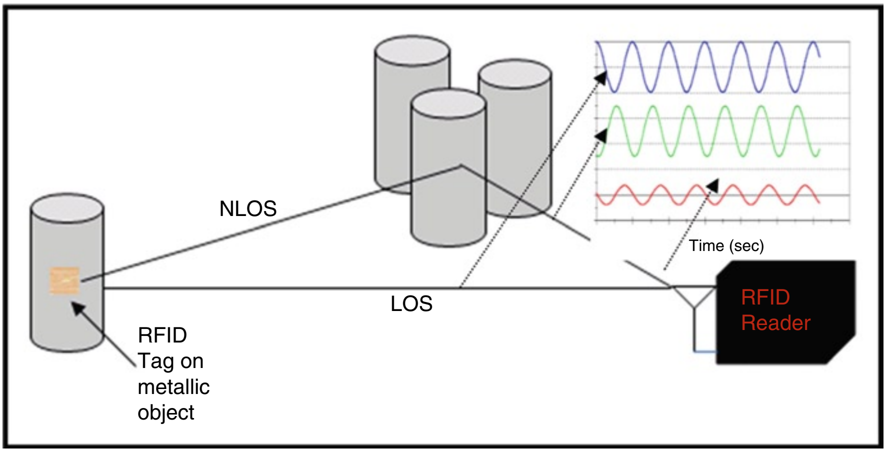

Fig. 2.2 Representation of multipath phenomenon in a wireless link on narrowband signals

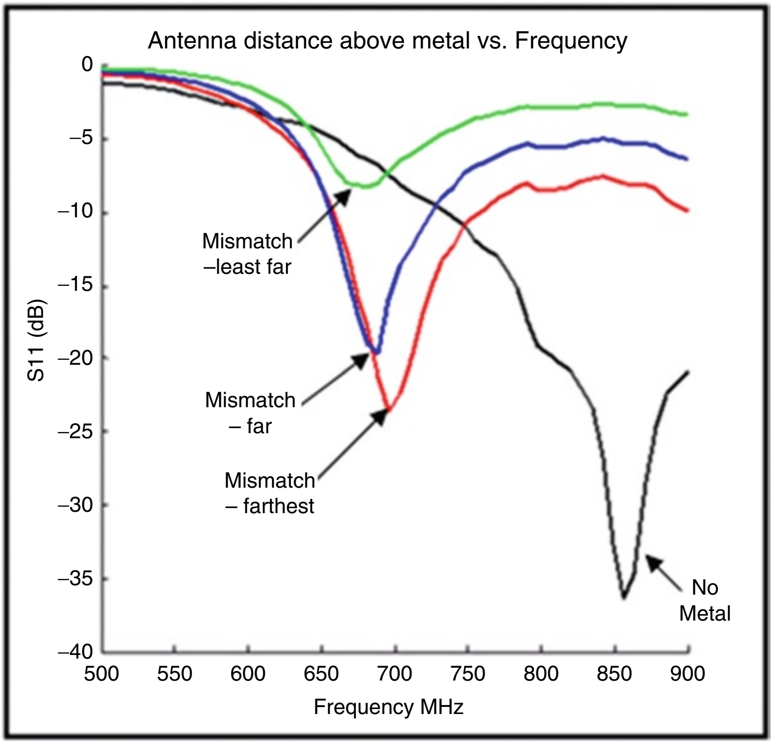

Fig. 2.3 Simulated response of a typical UHF tag over a metallic surface at various distances and as a function of frequency. There is a large impedance mismatch as the tag gets closer to the metallic object

shows the simulation results of reflection coefficient (S_{11}) versus frequency for a typical UHF passive tag at various distances from a metallic object.

As shown in the above simulation, the passive tag's antenna becomes de-tuned in the presence of a metallic object. The shift in resonance frequency from the tag's operating frequency (for example, 850 MHz) and hence the impedance mismatch between the tag and reader frequencies causes the tag to receive less energy from its reader. This will cause severe deterioration of the read range and therefore undermines the performance of the passive tag. Figure 2.4 shows the simulated radiation pattern of a UHF tag antenna in free space and on a metallic object.

As shown in Fig. 2.4, the performance response (radiation efficiency) of a UHF tag antenna severely degrades when it is located in the close vicinity of a metallic surface [2]. Benchmarking of UHF passive tags in the presence of conductive materials is presented in Sect. 2.3.

In theory HF passive tags (operating at 13.56 MHz) generally performs better, compared to UHF tags, around metallic surfaces due to their lower frequency and better penetration properties. However, these tags have shown serious limitations in read range when they are in contact or in close vicinity of a metallic surface. Figure 2.5 represents the read range performance of a commercial passive HF tag versus its distance from a metallic object.

As shown in Fig. 2.5, the read range of the HF passive RFID tag is noticeably reduced as the tag gets closer to the metallic object to a point that there is no read capability when the tag is placed directly on the metal. Since HF tags use inductive coupling to communicate with their reader, the "tag-on-metal" challenge for such tags can be explained by the Eddy current induced from metallic surface that is hit by the magnetic field generated between the tag and its reader. This induced Eddy current generates a magnetic field that is in opposite orientation of the original magnetic field between the tag and its reader (Lenz's law). Figure 2.6 illustrates the change in magnetic lines due to Eddy currents when tag is placed on a metallic object.

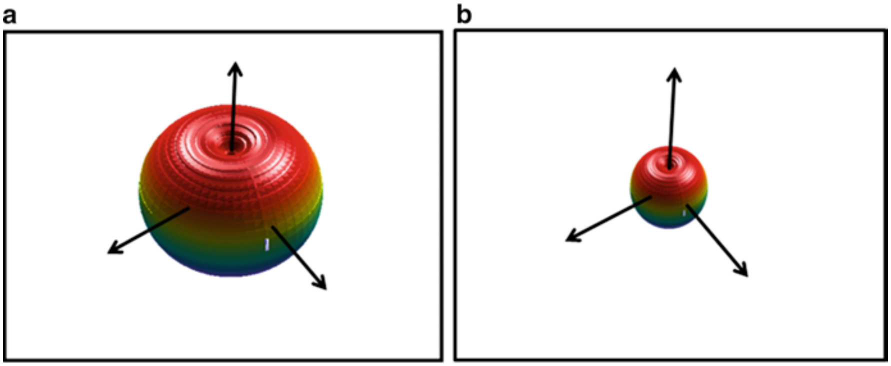

Fig. 2.4 Simulated radiation pattern of a UHF tag antenna in (**a**) free space and (**b**) on a metallic object

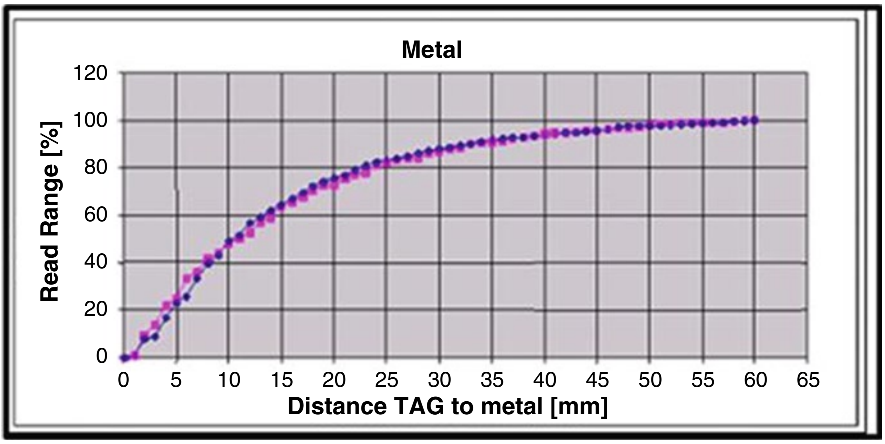

Fig. 2.5 Effect of metallic objects on tag-it transponders (Courtesy of texas instruments, reprinted with permission [3])

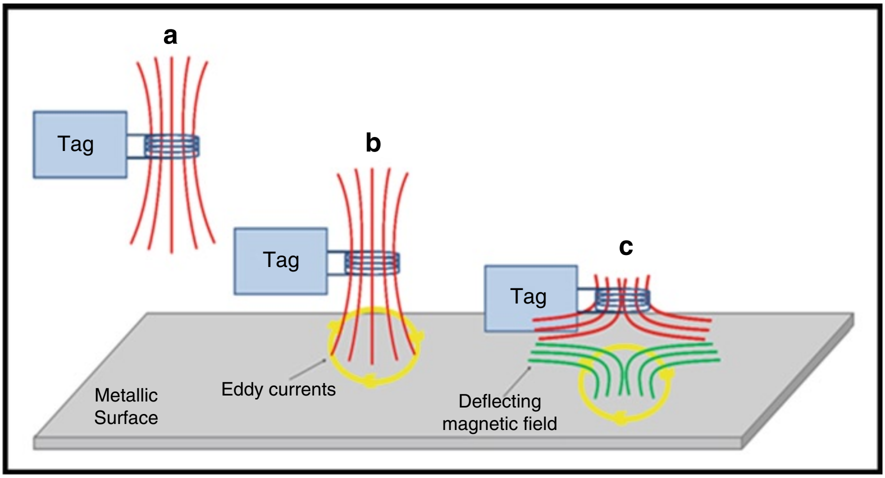

Fig. 2.6 Illustration of the change in magnetic lines as the tag gets closer to a metallic surface (**a**) tag in air, (**b**) tag near metal (**c**) tag on metal

The interference between the two magnetic fields results in magnetic deflection; causing poor performance of HF tags around metallic surfaces since the tag's coil will not receive enough magnetic flux to power up.

The fact that RFID tags perform poorly in the presence of metallic objects can be used in shielding/coupling attacks by adversaries. In shielding attacks the tag-reader communications is disrupted by wrapping the tagged item in a piece of aluminum foil, where in coupling attacks the tagged item is placed near a ferrous material that can detune the tag frequency to stop the communications with its reader.

2.2.2 Signal Detection and Jamming

Signal jamming and tampering is another serious concern in many RFID applications for monitoring assets of high value. Since the narrowband signals, used in some conventional RFID systems, have well defined RF energy in narrow frequency bands (as shown previously in Fig. 2.1) they are extremely vulnerable to intercept and detection. Therefore such signals can cause all kinds of security and privacy concerns such as sniffing/eavesdropping, cloning, tracking, and hindering or blocking service. The following section explains some of the common threats to narrowband RFID systems at physical layer level because of their highly detectable signal.

Sniffing/Eavesdropping Attacks

Eavesdropping is considered as passive attack where unauthorized RFID readers can capture the transmission between a tag and its reader from a long distance without the holder's knowledge [4]. There is a misconception that RFID systems that use magnetic coupling are relatively secure due to their short read range. For this situation, since the eavesdropper does not need to power up the tag, it can read tag information from a longer distance. In addition, high gain antennas or a set of antenna arrays can be used to detect tags at more extended ranges leading to violation of privacy. Some of these concerns include: accessing personal data from RFID enabled passports for identity theft, or obtaining account information from RFID enabled credit cards [4] (Fig. 2.7).

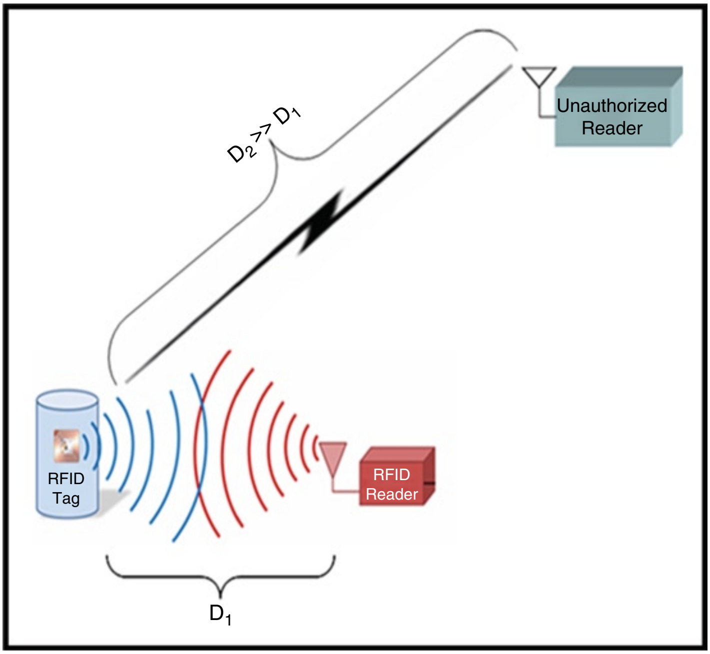

Fig. 2.7 Example of eavesdropping/sniffing attack where a sensitive unauthorized reader detects the tag information from a much longer distance (D_2) than its intended reader (D_1)

Spoofing/Cloning and Replay Attacks

Once the RFID signal is detected, tag information can be copied to an unauthorized blank tag by adversaries, called cloning [5, 6]. The cloned tag sends the same electromagnetic signal to the reader; this fake transmission fools the monitoring system thinking that a high value item is still in its place.

As shown in Fig. 2.8, first a sensitive unauthorized reader detects the tag information from a long distance (step 1); then the detected tag information is copied to a cloned tag (step 2); finally, the cloned tag replaces the stolen item and constantly sends its information about its presence to the authorized reader (step 3). This vulnerability could allow illegal access to all kinds of valuable and sensitive items/information that are secured by RFID monitoring. An example of spoofing attack would be the illegal modification of a passport-tag.

Relay Attacks

This type of attack is just like a man in the middle scenario, where one or multiple unauthorized readers can be placed between a tag and its reader to detect and change or counterfeit the transmitted signal between the tag and its legitimate reader [7]. This type of attack will fool the reader for similar scenarios that were described in the case of spoofing and cloning.

As shown in Fig. 2.9, the difference between the relay attack and spoofing attack (Fig. 2.8) is the information stored in the unauthorized tag. In spoofing attacks,

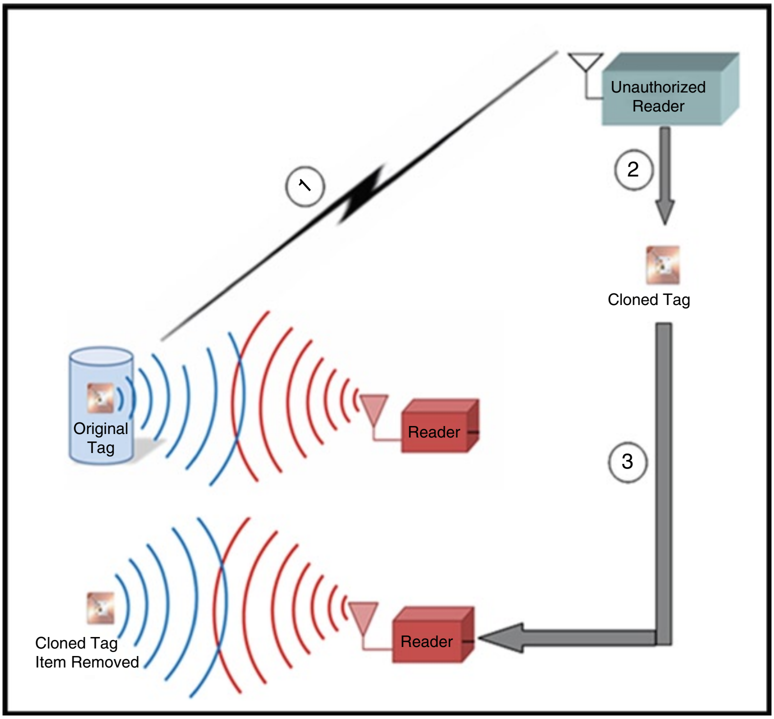

Fig. 2.8 Representation of spoofing attack in RFID systems

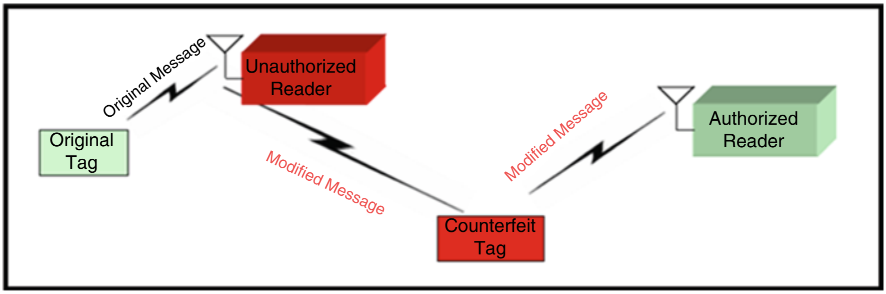

Fig. 2.9 Example of the relay attack, the original tag data is modified by the unauthorized reader and the counterfeit tag, before it gets to its authorized reader

the unauthorized tag has the exact same information as the original tag (cloned version), while in the relay attacks the unauthorized tag sends a different message to fool the authorized reader (Fig. 2.9).

Tracking Attacks

Unauthorized trackers can trace a tag transmission to the specific tagged item. Tracking attacks can help the hacker to locate and replace the tag for malicious activities or monitor the movement of assets and people for criminal reasons. This would be a serious concern in scenarios such as tagging of military assets that can be located and detected by adversaries.

Denial of Service (Jamming or Blocking)

Once the RFID transmission signal is detected, hackers can use interferers at the same operational frequency to jam the original signals and hinder the service to authorized users. Denial of service is an unavoidable problem in narrowband RFIDs since the tag/reader signal is very easily detectable (refer to Fig. 2.1).

Another form of denial of service is blocking the tag from receiving the reader powering signal in passive tags or blocking the transmission signals in the active tags by wrapping them in a metallic foil (refer to Figs. 2.2–2.6). The effects of metal on RFID tags were extensively discussed in Sect. 2.2.1, and is discussed further in the next section.

Denial of service attacks can help shoplifters to disrupt the service while stealing a product.

2.2.3 Signal Fading and Blockage

Fading, shadowing, and signal blockage is commonly found in narrowband communication systems. Walls, machinery, and foliage, can result in loss of signal in narrowband RFID systems making them unreliable for real-time monitoring applications. Furthermore, for unauthorized access to an RFID tagged item, the item can be placed in a metallic container or simply wrapped in an aluminum foil. The metallic enclosure creates a Faraday cage shield so the RFID tag becomes unreadable. This phenomenon can be shown by calculating the skin depth of the metallic shield enclosing the tag. Skin depth is a representation for penetration depth of electromagnetic signals within a conductor, given by (2.1).

$$\delta_s = \sqrt{\frac{2}{\omega.\mu.\sigma}} \tag{2.1}$$

where: δ_s is skin depth (m), ω is the angular frequency (rad/s) equal to $2.\pi.f(Hz)$, μ is the permittivity (H/m), and σ is the conductivity (mho/m). Based on the values of conductivity and permeability from [7], the skin depth for aluminum in 900 MHz (UHF) RFID tags is around 2.5 μm. Since a thin aluminum foil has about 200 μm thickness, the depth of penetration of 2.5 μm makes aluminum foils opaque to narrowband signals at UHF frequencies.

Using the skin depth equation above, we can see that HF and LF tags have higher skin depth and therefore, better chance of penetrating through metal. For example, a typical LF tag with frequency of 132 KHz, will have a skin depth of 206 μm that can barely pass the aluminum foil obstruction. It's important to mention that penetration through other materials including various metals depends on their conductivity and permittivity and can be calculated from (2.1) using available data for μ and σ of various materials in [8].

2.2.4 High Power Used by Active Tags

As explained in the previous chapter, active RFID tags are fully powered transponders that require an internal energy source to power up their on-board electronics such as RF transceivers, microcontrollers or processors, memories, and other sensors integrated with them. This class of tags typically consumes a large amount of power for achieving data transmission to long ranges with high data rates. Most of the power used by an active tag is used by the transceiver and microcontroller/microprocessor blocks. The transceiver circuitry in active tags consumes a large amount of energy in standby mode in order to receive every incoming signal. Although the state-of-the-art energy storage systems such as 1 cm^2 lithium battery can supply several years of continuous power supply at 10 μW, the standby power of the transceiver circuit in most active tags exceeds 10 μW. Hence, the several years of power provided by the battery will last only months or days for typical active tags (depending on the level of information they provide and the number of times they transmit in a day).

It's also important to emphasize that the transceiver circuitry in narrowband active tags are complex with many components that adds to the size, and power consumption of the tag. These components are specific to narrowband tags since tag-reader communications uses a specific carrier frequency, therefore, mixers and local oscillators are needed to translate the carrier frequency to baseband and the need for carrier recovery stage at the receiver end.

The high power consumption in narrowband active tags leads to the following disadvantages in their usage:

- Large tag size
- High cost of production
- Low reliability due to limited operational lifetime
- Long term and expensive periodic maintenance for changing tag batteries

Each of the above parameters plays an important role in the effectiveness of active tags for various applications. As a general rule, although active tags are designed for longer ranges, long-range communication can soon drain the power in the tag, and thus make monitoring quite unreliable.

2.2.5 Limited Range for Passive Tags

Since passive tags do not have an internal source of power and collect energy from their reader signaling, their communications range is very limited. In the passive tag category, the UHF and microwave tags have longer read ranges than the LF and HF tags. This is due to the fact that the operation of microwave and UHF tags is based on the far field communications, because the distance between the tag and reader antenna is typically longer than one wavelength in such frequencies (33 cm for UHF, and 12 cm for microwave tags) (Fig. 2.10).

In far field communications, the power in the transmitted signal decays in proportion to the square of distance from the antenna, where in near field communications (LF and HF tags) the signal power decays as the cube of the distance from antenna as shown in (2.2) and (2.3) respectively [9].

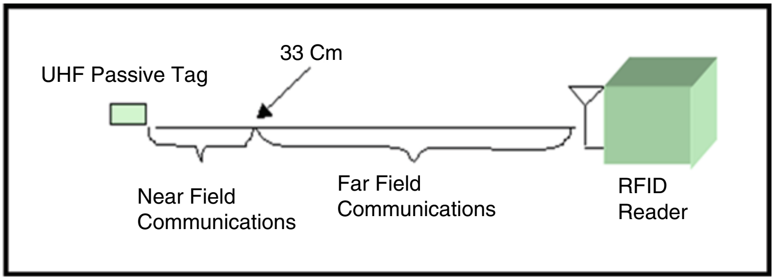

Fig. 2.10 Illustration of near field, and far field propagation modes for UHF passive tags. The near field-far field boundary (33 cm) is defined by one wavelength of the tag's operating frequency

Table 2.1 Forward link (reader-to-tag) budget analysis of a typical passive UHF tag at 915 MHz operating frequency

Reader transmit power	30 dBm
Aperture and path loss (3 m)	–41 dB
Reader transmit antenna gain	6 dBi
Tag antenna gain	2 dBi
Received power at tag	–3 dBm
Required power to activate the tag	–10 dBm
Link margin	+7 dB

$$P_{tag} \alpha \frac{1}{d^2} \tag{2.2}$$

$$P_{tag} \alpha \frac{1}{d^3} \tag{2.3}$$

where P_{tag} depicts the power received at the tag from its reader, and d is the distance between the tag and its reader.

Although UHF tags have longer communication range compared to lower frequency passive tags, their read range is still not acceptable for many applications. Link budget analysis of the forward link (reader-to-tag) for a typical UHF tag in Table 2.1 shows that under regulatory restrictions at a 3 m distance, the forward link margin is marginal (about 7 dB). This theoretical margin is based on the assumption that tag-reader communications occur in free space. In many practical scenarios, the 7 dB margin can easily be reduced to an even lower number, often by many factors, in real environments. The environmental factors affecting the tag performance include the presence of interferers, conductive and absorptive materials such as metal and liquids respectively, diffraction, and shadowing effects. The decrease in forward link margin demands even shorter distances between UHF passive tags and readers for reliable communications.

The calculations in Table 2.1 is based on the following operating parameters:

- Reader transmit power at 1 W (maximum FCC limit)
- Free space path loss at 3 m per (2.4)

$$P_r = P_{tx} \frac{A_e}{4\pi d^2} \tag{2.4}$$

  where P_r is the received power at the tag, P_{tx} is the transmitted power from the reader, A_e is the effective aperture equal to $\frac{\lambda^2}{4\pi}$, and d is the distance between the tag and its reader.
- Reader antenna is assumed to be isotropic with 6 dBi gain.
- Tag antenna is assumed to be isotropic with 2 dBi gain.
- Power required by the tag is 100μ Watt limited by silicon process. Typically, CMOS process can reduce the power requirement of the tag.

Although forward link (reader-to-tag) in UHF passive tags is limited to short ranges (< 3 m), the reverse link (tag-to-reader) is only limited to the reader sensitivity.

Table 2.2 Reverse link (tag-to-reader) budget analysis of a typical passive UHF tag at 915 MHz operating frequency

Tag incident power	–3 dBm
Aperture and path loss (3 m)	–41 dB
Tag antenna gain	2 dBi
Reader receive antenna gain	6 dBi
Tag modulation loss	–6 dB
Received power at reader	–42 dBm
Reader sensitivity	–100 dBm
Link margin	+58 dB

Sensitive readers can pick up signals as low as –90 to –110 dBm, so the reverse link margin could be very large as shown in Table 2.2.

The numbers in Table 2.2 is based on the following operating parameters:

- Tag incident power of –3 dBm (from Table 2.1)
- Symmetric path loss for forward and reverse links
- Tag modulation loss of –6 dB defined by (2.5):

$$K = \alpha \left| \rho_1 - \rho_2 \right|^2 \tag{2.5}$$

where K represents the tag modulation loss, α modulation coefficient, ρ_1 and ρ_2 are tag reflection coefficients.

As shown in Table 2.2, the reverse link has a very large margin (58 dB), hence the UHF reader is capable of reading a passive tag from much longer distance compared to the distance it can power up the tag. So the limitation in range for UHF passive tags is really related to their forward link. If UHF tags can be powered up more efficiently, sensitive readers can pick up tag's backscattered signals from very far distances (Km range, with a reader sensitivity of –100 dBm). This can cause a vulnerability in detecting tags by unauthorized readers from long distances (refer to Fig. 2.7).

2.2.6 Limitations to Worldwide Operation

Operation of the currently available RFID systems is limited to the specific narrowband frequencies used by the readers and transponders. Since the UHF tags operate in unlicensed ISM band, EPCglobal (worldwide RFID governing body) has rules for regulating the use of such frequencies around the world. Table 2.3, shows the UHF frequency allocations assigned by EPCglobal for various regions of the world [10, 11].

As shown in the Table 2.3, some frequencies are not available in different parts of the world, so there is no global solution for narrowband RFIDs and the tags operating frequency needs to be modified based on the specific region that they will be operating at.

Table 2.3 UHF operating frequency regulatory specifications for various countries

Country	Frequency band
America	902–928 MHz
Australia	918–926 MHz
Argentina	902–928 MHz
Brazil	902–928 MHz
China	No allocations yet
Hong Kong	920–925 MHz
India	865–867 MHz
Japan	950–956 MHz (Experimental purposes only)
Korea	910–914 MHz
Peru	902–928 MHz
Singapore	923–925 MHz

2.3 Performance Benchmark of UHF Passive Tags

The discussions in Sect. 2.2 revealed some theoretical limitations for the conventional tags that operate based on narrowband signaling. However, their true capabilities and limitations need to be evaluated in real world scenarios for a better understanding of their practicality in various applications. In this section we present a comprehensive performance benchmark of Commercial-Off-the-Shelf (COTS) RF tags to determine how they perform in the presence of conductive and dielectric materials such as metals and water, respectively. The benchmark presented in this section only covers the performance of some of the conventional UHF passive tags due to their popularity in many applications, and the fact that their performance depends heavily with respect to their environment. The benchmarks presented in sections 2.3.1 and 2.3.2 are excerpts from a report based on a previous research taken in University of Kansas for RFID Alliance Lab.[1] Although our main interest in this section is to show performance benchmarks of UHF tags with respect to metals and liquids, more interesting benchmarking information with respect to other important parameters such as orientation sensitivity, read in isolation and population, and variance of tags consistency is available in the report from University of Kansas [12, 13].

2.3.1 *Read Performance near Metal and Water*

As discussed earlier, the presence of a material near tags changes the characteristics of the tags antenna. The materials that are common and pose greater challenges to tag

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[1] Courtesy of Karthik Ramakrishnan from University of Kansas [12]. Portions reprinted with permission from "Performance Benchmarks for Passive UHF RFID Tags" Master's Thesis by Karthik Ramakrishnan, University of Kansas, 2003.

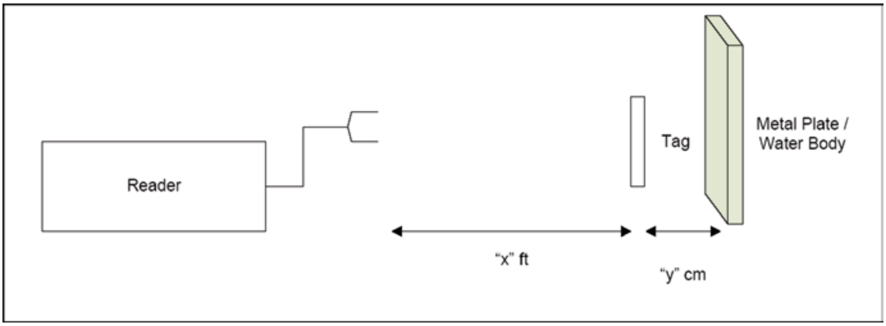

Fig. 2.11 Test setup for performance in front of materials

performance are metal and water. Water and metal affect tag performance in a number of ways. They provide multi-path and create fading zones. In fact, metals can be used to boost the performance of tags. The presence of high-dielectric material in the near field of the tag causes detuning of the antenna, so the antenna would resonate at a lower frequency. The presence of material changes the impedance bandwidth of the antenna and reduces the power transfer efficiency. The benchmarks in this section are aimed at studying the effects of tag performance near these materials.

2.3.1.1 Test Procedure

In this experiment the setup shown in Fig. 2.11 was used to evaluate the performance of UHF passive tags in the presence of conductive or absorptive materials.

The median tag from each tag model should be oriented at their best possible orientation in front of a metal plate whose size is comparable to wavelength. If the testing is done in front of water, a water body whose size is again comparable to wavelength should be used. The attenuation at which the tag becomes unreadable should be measured at various separations from the metal/water. Small separations between the tag and the material are the most interesting and most useful regions where the benchmark should be measured (as the tags are generally stuck on the materials). The attenuation is increased slowly until the tag becomes unreadable. This attenuation value should be measured for different separation between tag and material. The following test parameters should be considered for this benchmark:

- Separation range
- Separation step size
- Number of attempts done by the reader
- Attenuation step size – increments in attenuation
- Best orientation of the tag
- Separation between the reader and tag

Since the metric is an attenuation value at a particular separation, it is recommended that at least a few hundred read attempts are to be performed before assuming that the response rate has gone down to 0%. For statistical accuracy, the

Table 2.4 Parameters for read performance in front of metal/water

Test parameter	Parameter value
Environment	Free-air
Reader model	Class 0 – Matrics AR 400 Class 1 – Alien 9780
Reader software version	Class 0 – 03.01.09 Class 1 – 3.7.3
Antenna type	Bi-static and circular polarized
Number of antennas	1
Protocol of the tag	EPC Class 0/EPC Class 1
Multi-protocol reader settings	Scans only Class 0/Class 1 depending on protocol of the tag
Cables to connect antenna and reader	Factory default
Maximum power	32.5 dB
Application	Custom software on reader
Separation between tag and reader	34 in.
Separation range from materials	Metal – 0–2 cm Water – 0.55–2.55 cm
Separation step size	0.24 cm
Number of attempts	100
Attenuation step size	0.1 dB
Best orientation of the tag	(0,0)

number of attempts should be higher. The testing should be done in non-noisy environments, ideally, anechoic chamber is preferred.

2.3.1.2 Experiment

We placed the tag in front of the reader antenna at a distance of 3 ft as shown in Fig. 2.11. The tag and the material were separated in free-air. The material for the experiment was a large flat piece of steel ($\approx 2\lambda x 5\lambda$) in front of metal while it was a 10-gallon aquarium filled with water and in front of the water. The separation was varied from 0 to 2 cm in steps of 2.5 mm from the material. It should be noted that the thickness of the glass plate (0.55 cm) has to be taken into account when the experiment is done in front of an aquarium. The attenuation at which the tag became unreadable for each separation was noted. Table 2.4 lists the parameters that were used for both the experiments in front of metal and water. Different readers were used for reading Class 0 and Class 1 tags.

2.3.1.3 Results and Lessons Learned

Tags in Front of Metal

Figure 2.12 shows the comparison of performance for four Class 0 tags in front of metal.

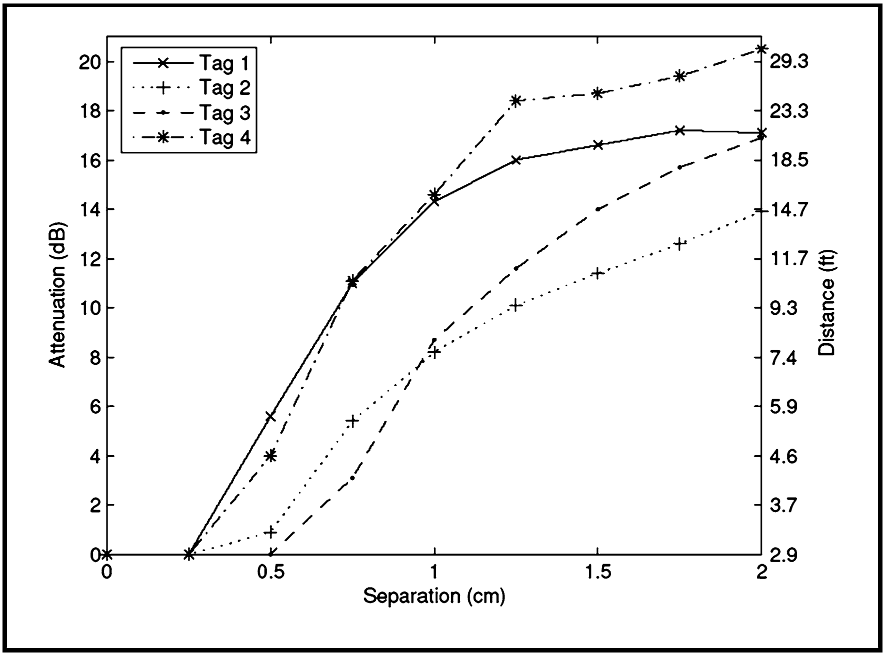

Fig. 2.12 Tag performance in front of metal

As seen in Fig. 2.12, Tag 1 and Tag 4 have better performance than the other two tags starting from a separation of 5 mm. It should be noted that Tag 1 design is supposed to work better in reflective environments and as can be seen from the experiments it turns out to be the best in front of metal when compared to the Class 0 tags. The performance of Tag 4, a dual dipole design is comparable to Tag 1. Even in our free-air experiments, Tag 4 was a fundamentally better tag compared to other tags.

It can be seen that, all the tested tags were unreadable at a separation of 2.5 mm from metal. Some of the tags had a good performance at a separation of even 5 mm from metal.

Tags in Front of Water

Figure 2.13 shows a selection of Class 1 tags that we had tested in front of water.

As can be seen in Fig. 2.12, Tag 4 is the best performing in front of water at a distance of 0.8 mm. However, it should be noted that the same tag is not the best performer in free air. Tag 3 is a better performer in free air but is highly detuned when it comes in front of water. Tag 2 is the worst among the compared Class 1 tags. This showed that some of the tags were tuned to work in front of water but it should be noted that none of the tested tags worked at a separation of 0.55 mm from water (when the tags were directly on the container).

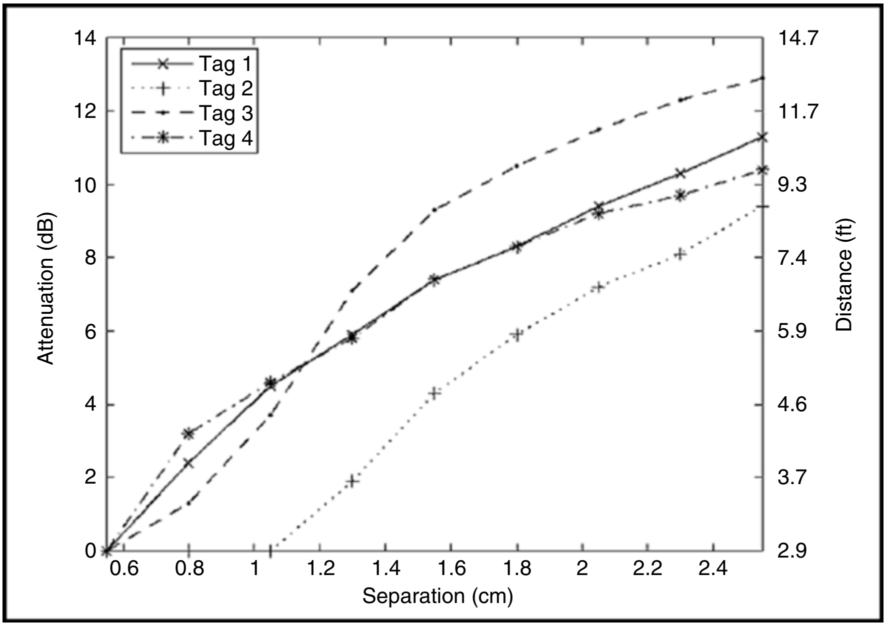

Fig. 2.13 Class 1 tag performance in front of water

2.3.2 *Frequency Dependent Performance*

As seen in the previous section, presence of materials near tags affects the frequency response of the tags. The objective of this benchmark is to determine the changes in the frequency response of tags near materials.

2.3.2.1 Test Procedure

The same test procedure described in Sect. 2.3.1 should be used for this benchmark. The tag should be read at a fixed frequency and then the frequency is varied. The attenuation at which tag is unreadable is measured across all the frequencies of interest. The following test parameters should be considered for the benchmarks:

- Separation range
- Separation step size
- Number of attempts done by the reader
- Attenuation step size – increments in attenuation
- Fixed frequencies of interest
- Separation between the reader and tag
- Best orientation of the tag

Table 2.5 Parameters for frequency response in front of materials

Test parameter	Parameter value
Environment	Free-air
Reader model	Thingmagic Mercury 4
Reader software version	2.4.22
Antenna type	Bi-static and circular polarized
Number of antennas	1
Protocol of the tag	EPC Class 0/EPC Class 1
Multi-protocol reader settings	Scans only Class 0/Class 1 depending on protocol of the tag
Cables to connect antenna and reader	Factory default
Maximum power	32.5 dB
Application	Custom software on reader
Separation between tag and reader	34 in.
Separation range from materials	Metal – 0–2 cm Water – 0.55–2.55 cm
Separation step size	0.25 cm
Number of attempts	1,000
Attenuation step size	0.1 dB
Best orientation of the tag	(0,0)

The higher the number of frequencies under consideration, higher would be the resolution of the frequency response.

2.3.2.2 Experiment

The experiment parameters for the frequency response in the presence of metal and water are summarized in Table 2.5.

The experiment described in Sect. 2.3.1 was repeated when the reader was programmed to do the reads in a single, fixed frequency and then the frequency was varied. The parameters used for this experiment are listed in Table 2.5.

2.3.2.3 Results and Lessons Learned

Tags in Front of Metal

It was seen in Sect. 2.2.6 that the ISM band in UHF frequencies varies between different countries. The ISM band frequencies in various countries are 860–868 MHz in Europe, 902–928 MHz in USA, and 950–956 MHz in Japan. Most of the antennas that are used for tags are resonant antennas and it is widely known that the presence of high dielectric like water near antennas changes their resonant frequency. Thus, if a tag is to be read globally, they should perform well across all these frequencies.

In this benchmark, the experiment was performed at 902 MHz, 915 MHz, 928 MHz, and 955 MHz. We measured the attenuation at which the response rate

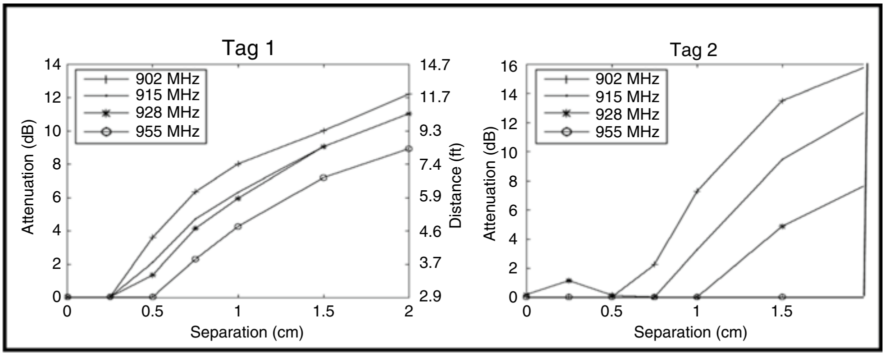

Fig. 2.14 Comparison of tags in front of metal based on operating frequency

goes down to 0% across different frequencies. Figure 2.14 shows the frequency dependent performance of two different tags in front of metal.

It should be noted that Tags 1 and 2 are readable at all the frequencies in free-air. In front of metal, Tag 1 performs better at lower frequencies and degrades a little bit as the frequency is increased. This is typical performance of most of the tags near metal. However, as can be seen with Tag 2 there are drastic changes in performance with increase in frequency. At 2 cm separation, Tag 2 performs better than Tag 1 at 902 MHz but as can be seen, Tag 2 is unreadable at 955 MHz near metal. This means that if a metal product with Tag 2 on it is shipped from USA to Japan, it would be readable and would work when it is shipped but would be completely unreadable in Japan.

Tags in Front of Water

A similar observation was made with the above tags when they are in front of water. However, we observed one more interesting behavior of the frequency response in front of water.

The Fig. 2.14 shows two tags that have a similar behavior but different performance levels. In this Figure, the performance of the tags at different separation from water continer is shown. It can be clearly seen that both the tags have good performance at 955 MHz at a separation of 2.55 mm. As the separation is decreased, the performance degrades rapidly at 955 MHz compared to moderate decrease at other frequencies. This is a common behavior that we have observed for all the tags when the tags are in front of water. The performance rapidly decreases at higher frequencies whereas there is comparatively gradual decrease in performance at lower frequencies (Fig. 2.15).

Another observation about performance is that at small separations, Tag 1 still has some link margin at which the tag is still readable. Thus, it is quite evident that Tag 1 is better in terms of performance than Tag 2.

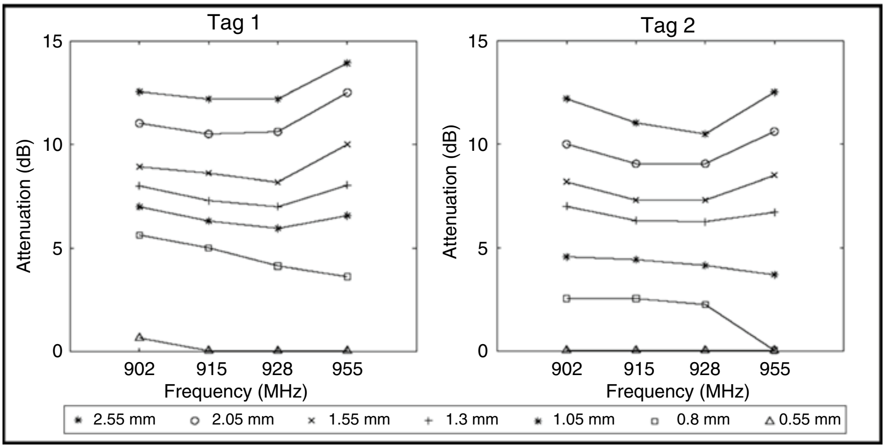

Fig. 2.15 Comparison of tags in front of water based on operating frequency

Frequency dependent analysis gives insight into the detuning effects of the antennas, permits a way to analyze better antenna designs for specific materials, and provides a performance criterion through which a globally visible tag can be developed.

2.4 Overview of Ultra-Wideband Technology

Many of the difficulties in tag-reader communications associated with narrowband signaling discussed earlier in this chapter can be addressed through the use of ultra-wideband (UWB) technology in new generations of RFID systems. In UWB signaling scheme, extremely narrow RF pulses are used to communicate between transmitters and receivers. The duration of UWB pulses are typically few hundred picoseconds to a few nanoseconds. These narrow pulses naturally generate very wide bandwidth in the range of few GHz in frequency domain as shown in Fig. 2.16.

Referring to Fig. 2.16, as the frequency spectra of the UWB pulses are spread out over many GHz of bandwidth with a power spectral density in the noise floor, trans-

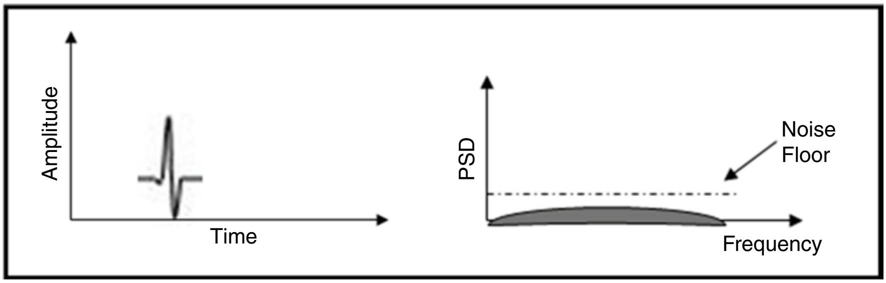

Fig. 2.16 A typical UWB pulse (*left*) in time domain (*right*) in frequency domain

mitted pulses are not only very difficult to detect when transmitted with a certain time-space coding, but are effectively invisible to unauthorized readers. In addition the extremely wide spectrum of UWB pulses generates large channel capacity and a robust link with respect to multi-path and diffraction in harsh RF propagation environments such as cluttered and reflective environments. Figure 2.17 shows a comparison of frequency spectrum of narrowband and UWB signals in a multipath channel, where signal fading is visible in narrowband signals and UWB spectrum keeps a steady signature.

Another advantage of UWB systems is their simpler transceiver circuitry due to carrierless transmissions. Therefore, UWB systems can be developed with smaller form factor and lower cost compared to narrowband systems.

It's important to note that despite the many advantages that come with the nature of UWB signaling in communications systems, they face serious technical challenges. These challenges include: synchronization between the transmitter and receiver for narrow RF pulses, difficulty in sampling such short duration pulses, and lack of similarity between the transmitted and received pulses. Figure 2.18 shows an example of transmitted and received UWB pulses in a multipath channel that makes the detection difficult using conventional pulse detectors or classical matched filters (CMF).

Ultra-wideband conceptually is not a new technology as it was first demonstrated by Guglielmo Marconi in 1901 for transmitting the Morse code sequences across the Atlantic Ocean using spark gap radio transmitters [1]. This technology was heavily used in military radars back in late 1960s and gained its momentum after FCC's approval of the commercial applications of ultra-wideband in early 2002. FCC's approval of 7,500 MHz unlicensed frequency band for ultra-wideband systems allowed two different approaches to UWB signaling, single band and multiband. Single-band UWB approach is the traditional UWB where very short duration pulses (impulse radio) are transmitted where it occupies the entire spectrum with minimum bandwidth of 500 MHz and fractional bandwidth of larger than 20%. This is similar to time and frequency representations of a UWB signal shown earlier in Fig. 2.16. However, in another approach, referred to as the multi-band approach, multiple overlapping smaller bands with bandwidths greater than 500 MHz have been used to construct the UWB signaling; an example of a multi-band UWB spectrum is shown in the following Fig. 2.19.

As shown in the Fig. 2.19, multiband UWB approach has similarities to narrowband frequency hopping techniques. Although the two schools of thought are often skeptical of the other approach to UWB technology development, both approaches are technically viable and have their unique advantages and challenges. The supporters of the single-band approach believe that the high complexity of the multi-band systems due to complex Fast Fourier Transforms (FFT) makes multiband system more complex. While advocates of multi-band approach believe that their technique is easier to synchronize compared to very narrow radio impulses used at single-band approach.

Ultra-wideband technology is well discussed in various books and publications therefore; we won't go into the details of UWB technology in this book. However, we will focus our attention to the use of UWB signaling in RFID systems in the following chapters. The details of advantages of UWB signaling in RFID systems is

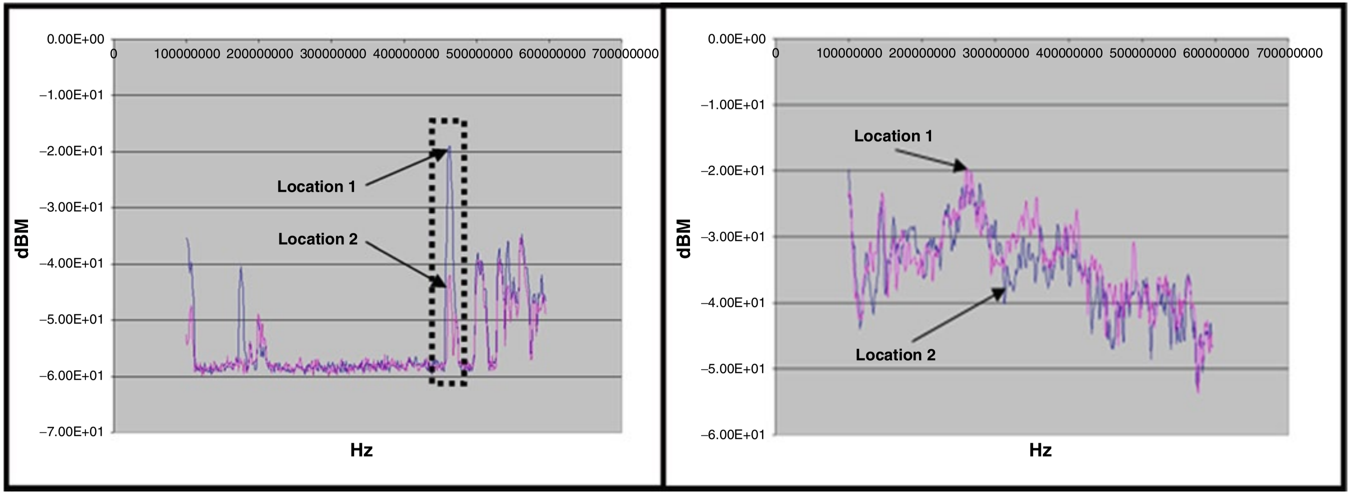

Fig. 2.17 Multipath effect on (*left*) narrowband signals, and (*right*) UWB signals. Please note that the vertical axis is not to the same scale for both graphs. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract, DE-AC52-07NA27344-LLNL-PRES-401143

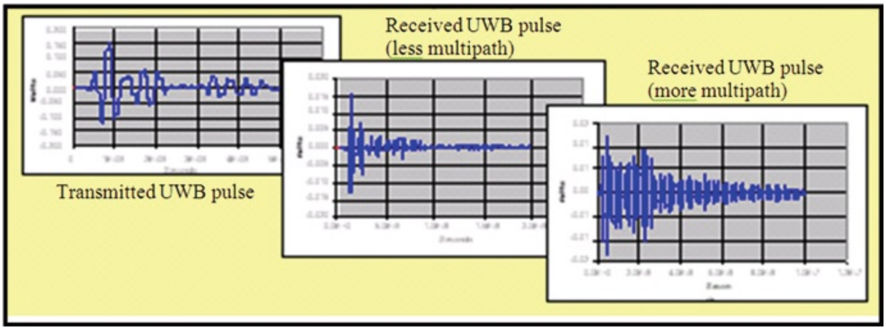

Fig. 2.18 Example of multipath effect on UWB signals. Pulses can get stretched heavily depending on the amount of multipath in the wireless channel[2]

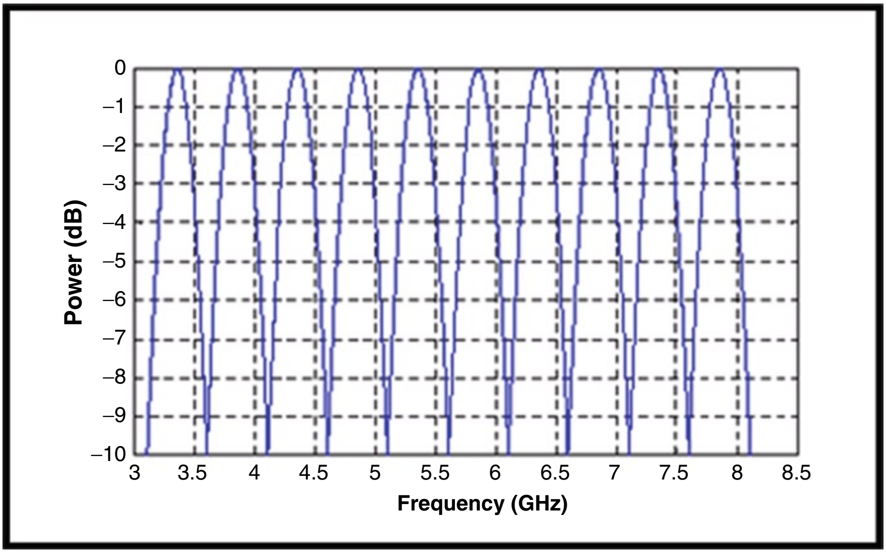

Fig. 2.19 Representation of UWB signaling in multi-band approach

discussed in Chap. 3, followed by implementation aspects of UWB signals in RFIDs in Chap. 4. A comprehensive discussion on UWB antennas for RFID systems is covered in Chap. 5 and applications of UWB RFID systems are discussed in Chap. 6.

For more detailed information on UWB technology, we encourage the reader to study some of the references listed in this chapter's bibliography section.

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[2] This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract, DE-AC52-07NA27344-LLNL-PRES-401143

2.5 Summary

Although narrowband RFIDs have reached a considerable level of maturity where they can be useful for many applications, the limitations posed by utilizing narrowband signaling for tag-reader communications limits their widespread adoption in some practical environments. In this chapter we covered the fundamental physical limitations that are caused by narrowband signaling scheme in tag-reader communications. The limitations that were discussed this chapter included: (1) security and privacy of tags due to various types of attacks including spoofing, cloning, and denial of service; (2) performance degradation in the presence of metals; (3) limited lifetime of active tags; (4) short range for passive tags; (5) and limitations to worldwide operations.

Also, in this chapter, to complete our discussions on limitations of narrowband signaling in conventional RFID systems, we presented results of a detailed report on benchmarking of some commercial narrowband UHF systems.

Finally, we ended the chapter with a brief overview of ultra-wideband technology to set the ground for later chapters for discussing more advanced topics such as advantages of UWB signaling for RFID systems, as well as UWB implementation aspects, and UWB antennas for RFIDs.

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Chapter 3
Improvements in RFID Physical Layer Using Ultra-wideband Signals

3.1 Introduction

Even though narrowband RFID systems are currently quite mature and effective in many applications, the limitations posed by narrowband signal characteristics (discussed in Chap. 2) makes them somewhat unreliable for use in certain practical environments [1]. Some of these limitations include:

- Difficulty to operate on/around metallic surfaces
- Privacy and security issues related to signal detection
- Signal blockage
- High power consumption by active tags
- Limited range of passive tags
- Limitations in worldwide operations

Although the state-of-the-art research in narrowband RFID systems has overcome some of these limitations, the use of ultra-wideband[1] (UWB) signaling for tag-reader communications could be another option to address many of these challenges. As we explained in Chap. 2, the nature of narrow RF pulses in UWB signals used as building blocks for tag-reader communications, offers some important advantages over conventional carrier based RF signaling. Therefore, UWB technology can be considered as a powerful complementary approach to the existing solutions to overcome some challenges of the conventional RFID systems. In this chapter we discuss the distinct advantages of UWB RFID systems over traditional RFID systems, such as improved security due to their low probability of intercept and detection (LPI/D) and resistance to jamming, relative immunity to multipath which results in improved performance in metallic environments, and simple hardware architecture resulting in lower production cost. Then we cover various UWB modulation techniques that can be used for tag-reader communications and discuss

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[1] (In this Chapter, UWB refers to impulse radio (IR-UWB) due to its simplicity for RFID implementation compared to multi-band UWB approach discussed in Chap. 2.)

F. Nekoogar and F. Dowla, *Ultra-Wideband Radio Frequency Identification Systems*,
DOI 10.1007/978-1-4419-9701-2_3,

the advantages and challenges of each one depending on the tags operational scenario and environment. Finally we conclude the chapter by a benchmarking report on the performance of two of the widely used commercial active UWB systems. The systems under evaluation are Sapphire DART system from MultiSpectral Solutions Inc. (a Zebra company) [2] and Precise Real-time Location System from Ubisense Ltd [3]. Although active UWB RFID systems have been used in healthcare and automotive industries, so far (at the time of preparing this manuscript) there is no commercial passive UWB RFID system.

3.2 UWB Signaling for RFID Systems

Unlike conventional narrowband RFID systems that use a strong signal with high power spectral density at a particular frequency, UWB RFIDs use low power RF pulses that operate over several GHz of frequency with low power spectral density, shown in Fig. 3.1 [4].

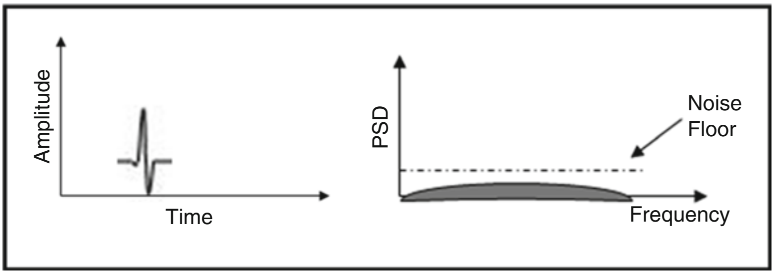

Fig. 3.1 A UWB pulse in time domain and frequency domain

The frequency diversity achieved by the transmission of extremely narrow pulses makes UWB signals viable candidates for RFID systems. In the next subsections we discuss the advantages of UWB signaling for RFID systems in detail along with the explanation of how the RF impulses can address the specific challenges that are faced by conventional narrowband RFID systems at the physical layer.

3.2.1 Improved Performance Around Metallic Surfaces

RFID tags that use UWB signaling could potentially have better performance in obstructed channels and around metallic surfaces. The extremely narrow width of UWB pulses makes them less sensitive to multiple reflections from surrounding objects (called multipath phenomenon). This relative immunity of UWB pulses with respect to multipath effect is because the non-line-of-sight (NLOS) pulse has an extremely short window of opportunity (equal to the pulse width) to be destructively added to the line-of-sight (LOS) pulse and cause signal degradation as shown in Fig. 3.2.

Another important point to consider is that since UWB RFID systems do not rely on inductive coupling, magnetic field effects such as induced and interfering Eddy currents have little or no effect when UWB tags are placed directly on metallic objects.

To explore the performance characteristics of UWB antennas in the presence of metallic objects, we compare the performance of a UWB 10:1 bidirectional spiral antenna (Fig. 3.3) at various distances with respect to a metallic plate.[2]

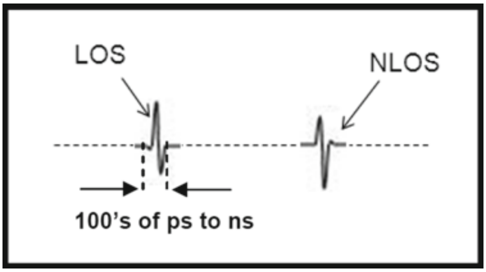

Fig. 3.2 Representation of multipath effect on ultra-wideband pulses

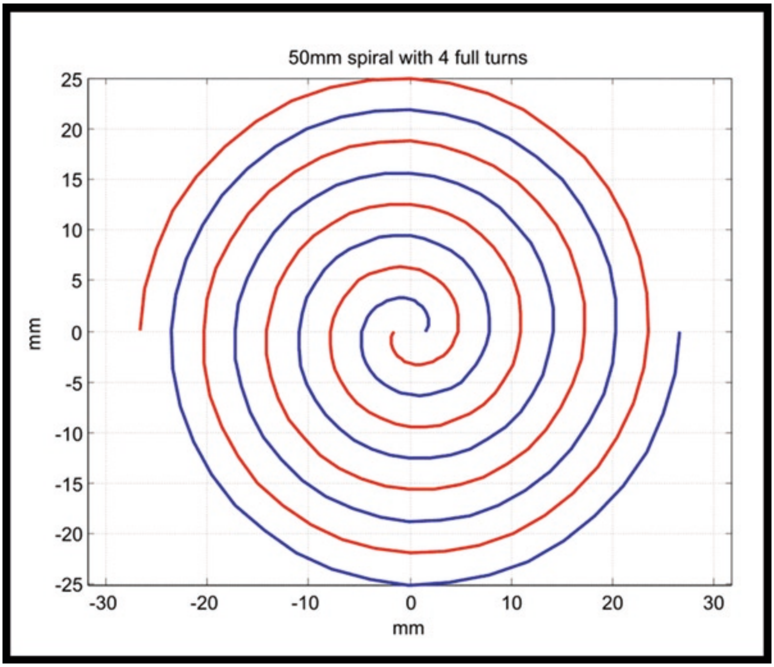

Fig. 3.3 A two-arm center-fed Archimedean spiral antenna with 4 full turns

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[2] (Courtesy of Prof. Sergey Makarov of Worcester Polytechnique Institute (WPI).).

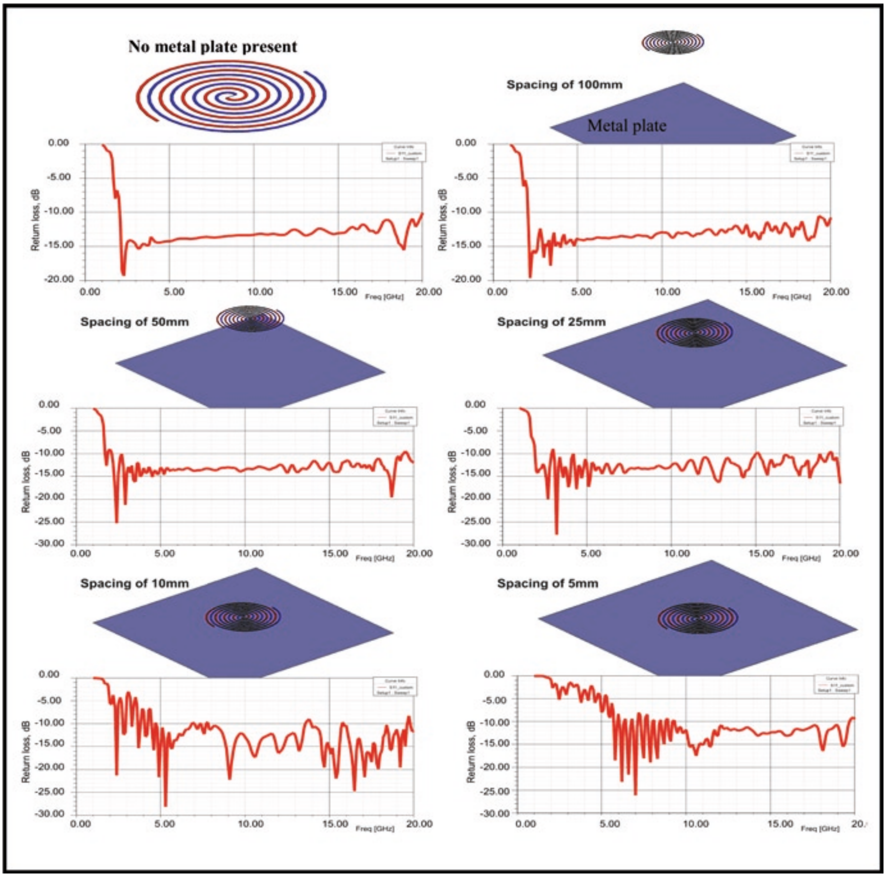

Fig. 3.4 Return loss of the 50 mm UWB spiral antenna as a function of frequency at various separation distances from the ground plane

Generally speaking spiral antennas have relatively wide impedance bandwidth (in excess of 3:1), when matched to 300 Ω, and rather controllable pattern variations over their operating band with circular polarization. More comprehensive reviews on spiral antennas are available in [5, 6]. Figure 3.4 shows the simulation results for a typical UWB antenna (50 mm spiral antenna) above a 150 mm by 150 mm perfect electric conductor (PEC) ground plane with separation distances of: Infinity (no ground plane), 100 mm, 50 mm, 25 mm, 10 mm, and 5 mm.

The Fig. 3.4 shows that the spiral antenna without the ground plane has the 10:1 impedance bandwidth. When the ground plane is present, the bandwidth does not significantly change as long as the separation distance is less than 50 mm. Even at smaller separation distances of 25, 10, and 5 mm, the antenna maintains a significant part of its impedance bandwidth. This means that the UWB antenna under simulation is less sensitive to the presence of the ground plane. Further simulations have shown that the UWB antenna keeps its performance at higher frequencies also.

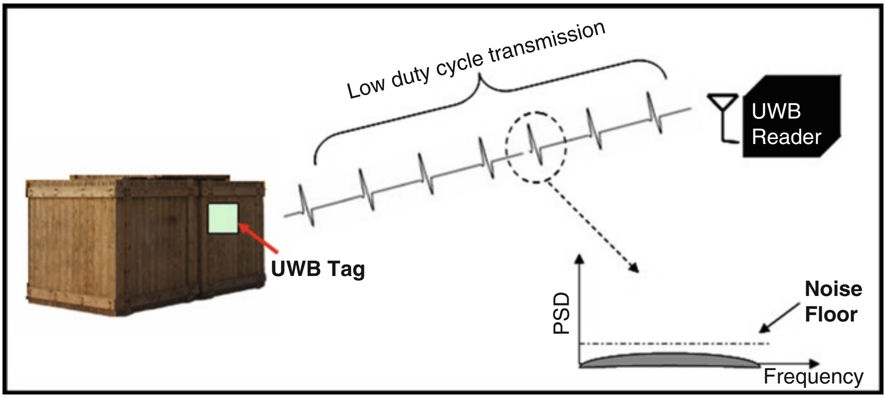

Fig. 3.5 UWB tag and readers communicate using narrow pulses with medium to high peak power transmission and low duty cycle, resulting in extremely low average transmission power

3.2.2 Immunity to Active and Passive Attacks

UWB RFID's have an inherent physical layer security with respect to eavesdropping and jamming. The stream of narrow pulses used for tag-reader communications in such systems have low duty cycle which results in low average transmission power (usually few microwatts) making them extremely difficult to detect. Therefore, UWB RFID systems are less susceptible to vulnerabilities such as: eavesdropping, spoofing, cloning, as well as replay attacks when compared to their narrowband counterparts. In addition, the frequency diversity that exists in the wide bandwidth of UWB pulses makes them resistant to jamming and interference, and protects them from intentional disruption and denial of service attacks Fig. 3.5.

The low average transmit power of UWB signals causes them to reside below the noise floor of a typical narrowband RFID reader. Therefore, UWB emissions or backscattered signals from active and passive RFID systems are difficult to detect, intercept, or modify by an unauthorized reader. Furthermore, UWB signals can be encrypted at physical layer by using various types of pulse modulation to make it even more difficult for unauthorized readers to detect or decode the messages from UWB RFIDs. This concept is described in more detail in the following section.

3.2.3 Encryption at Physical Layer Using Pulse Modulation Techniques

RFID systems with UWB signaling can be made secure by various types of pulse coding used in modulation of the data bits transmitted between tags and readers [7–9]. The pulse coding provides UWB RFID's with additional protection against

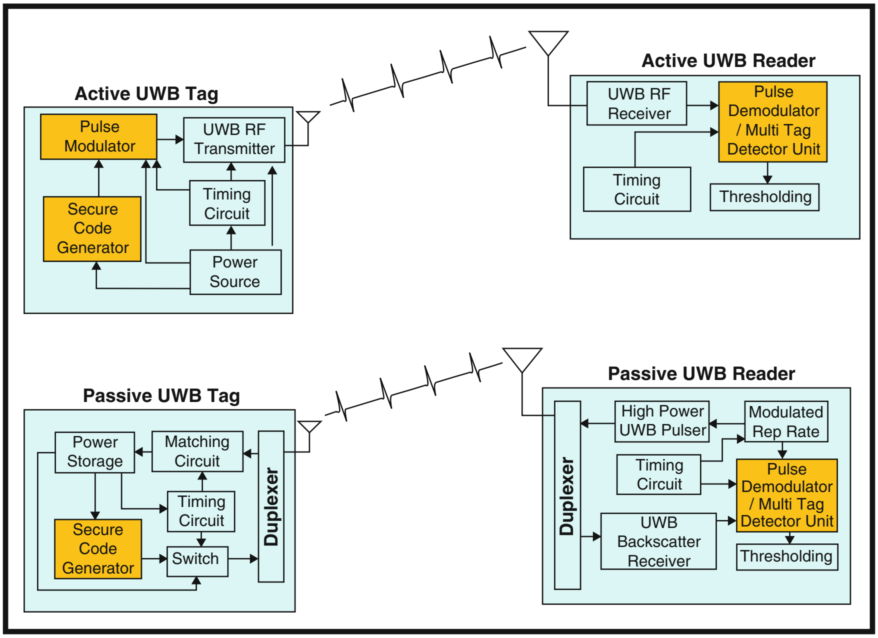

Fig. 3.6 System block diagram of a secured (*Top*) active UWB RFID (*Bottom*) passive UWB RFID highlighting the physical layer encryption feature

all kinds of active and passive attacks discussed in Chap. 2. Furthermore, pulse modulation techniques eliminate the need for the computationally intensive and power hungry digital cryptography algorithms such as hashes and block ciphers [8] that is desired to be used in traditional RFID systems. Various pulse coding parameters used in UWB modulation schemes can be used as a private key between the tag and its reader to prevent unauthorized readers from obtaining the tagged item's information in a detected signal (if the signal can be detected at all!!). Some of the parameters that can be used in pulse modulation techniques are pulse shape, timing between pulses, pulse polarity, and pulse amplitude. We discuss some of the UWB modulation schemes appropriate for UWB RFID systems in Sect. 3.4. Figure 3.6 represents block diagrams of secured UWB RFID active and passive systems.

As shown in Fig. 3.6, the secret pulse modulation codes offer "cryptography" at physical layer by transmitting data bits that are securely modulated. This secure data transmission offers low system latency in tag-reader communications, and eliminates the need for large silicon area that was required by cryptography blocks in narrowband secure tags.

Current research has shown that to eavesdrop a tag that is modulated with a 16-bit UWB code, sophisticated and high-end communications equipment are required [8]. Therefore, listening to such a tag becomes difficult even in the absence of typical cryptographic ciphers. However, depending on the needs and the availability of power and silicon area for specific applications, digital cryptography could be used in addition to UWB secret code modulation to provide additional security.

Furthermore, if the physical layer secret code is based on timing between UWB pulses such as pulse position or time hopping modulation, the jamming becomes extremely difficult. The reason is that the jammer has to distort pulses at specific positions in time, which requires expensive devices to transmit strong signals in GHz domain. We'll cover UWB modulation schemes that can be beneficial to RFID implementations in Sect. 3.4.

3.2.4 Capability to Detect Tags Behind Walls

Ultra-wideband RFID tags can be detected behind walls and enclosed environments. As we discussed earlier in Chap. 2, UWB signals cover a broad range of frequencies, hence the low frequency components of their spectrum makes them capable of effectively penetrating through a variety of materials. On the contrary, for narrowband signals to achieve the same bandwidth, they have to operate at higher center frequencies where the attenuation loss increases preventing them to penetrate most materials. The inverse relationship between the relative bandwidth and center frequency in UWB systems, defined in (3.1), implies that large bandwidth and high data rates can be achieved at low frequencies.

$$BW_{rel} = \frac{BW_{abs}}{f_c} \tag{3.1}$$

As shown in the above equation, for a fixed relative bandwidth, BW_{rel}, at low center frequencies, f_c, the absolute bandwidth, BW_{abs} should be large. Although studies have shown that certain frequencies in UWB signal spectra can be absorbed due to frequency-dependent dielectric characteristics of various walls [10], a UWB RFID reader detects the presence of pulse energy in time, not at any specific frequency. In addition, there is a consistent observation that narrow UWB pulses can pass through small gaps and cracks. One theory behind this observation is that since the energy is localized in UWB pulses, they can form a waveguide to penetrate through fine gaps. Examples of penetration through small cracks have been repeatedly reported in literature [11, 12]. This property helps detecting the presence or absence of UWB RFID tags inside buildings or containers (for inventory applications), under rubble (in search and rescue for disaster situations), through clothes in hospitals (for patient monitoring applications).

3.2.5 Accurate Tag Positioning Capability

As discussed in Chap. 2, the frequency diversity and large bandwidth of UWB signals allows for fine temporal and spatial resolution. This characteristic of UWB signals permits centimeter level accuracy in both outdoor and indoor localization of UWB RFID tags in all three dimensions. Simulations and limited experiments have

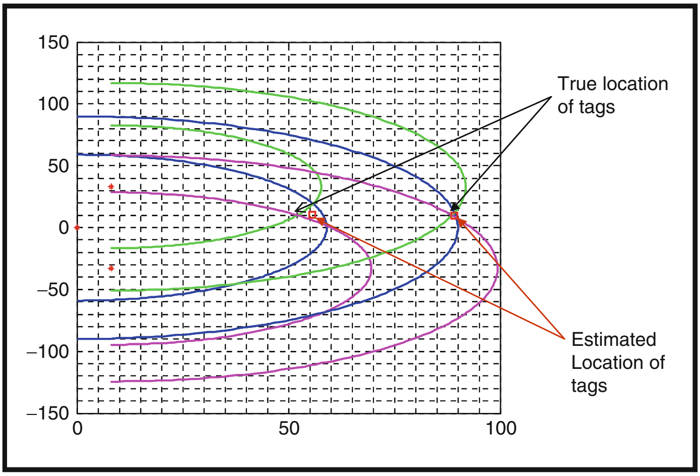

Fig. 3.7 Positioning accuracy is better than 3 in. with three readers[3]

shown that using ranging and time-of-arrival (TOA) techniques, UWB tags can be accurately located by three or more UWB readers [13].

Figures 3.7 and 3.8 show results for indoor positioning of prototype passive UWB tag (essentially a reflector) interrogated with 26 GHz UWB readers.

As shown in Fig. 3.7, tags can be located within 3 in. by using three readers. However positioning accuracy is expected to improve with four or five readers. Figure 3.8 shows simulation results of indoor localization of UWB tags using five readers.

As shown in Fig. 3.7, UWB tags can be accurately localized in all three dimensions by 5 readers in indoor channels. It's important to emphasize that accurate positioning does not always require multiple readers. A single reader on a moving platform can be used to detect the UWB signals from multiple angles and detect the range and direction of the strongest UWB signal for positioning a UWB tag.

3.2.6 Longer Battery Life for Active UWB Tags

Battery powered UWB RFID tags have longer lifetime compared to conventional narrowband active tags due to reduced power consumption of the UWB transmissions. Although UWB transmission between tags and readers can be either impulse-based (single-band) or carrier-based (multi-band), the impulse-based transmission seems advantageous in UWB RFIDs. The reason is that the low duty cycle pulses used in single band transmission, offers low average transmit power

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[3] This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract, DE-AC52-07NA27344-LLNL-PRES-401143

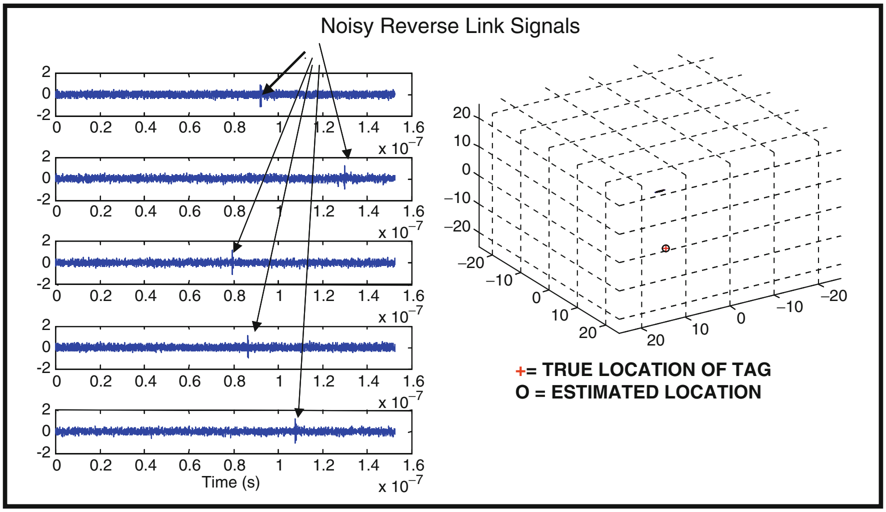

Fig. 3.8 Tag positioning algorithm and simulation experiments indicates that 5 readers are needed for accurate localization in (x,y,z)[4]

that can significantly reduce the tag power consumption and extend the battery life of active and semi-active UWB RFID tags.

Low duty cycle means that the UWB pulses or burst of pulses are short with a large space between them, resulting in extremely low average transmission power as shown in Fig. 3.9.

Another reason why low power transmission of UWB signals is acceptable is the fact that the fade margin requirement is smaller, a characteristic of wideband links. Laboratory experiments show about 5 dB fading in UWB transmission for indoor channels. Such a small fading margin, compared to 35 dB fading in narrowband systems can directly be translated to 30 dB reduction in transmit power for reliable communications between UWB tag and readers.

3.2.7 *Extended Range for Passive Tags with UWB Remote Powering*

RF signals can remotely power electronic circuits from a remote distance. The remote powering distance is highly dependent on the voltage level at the storage capacitors after overcoming the diode drop in electronic circuits. Comparing UWB and narrowband signals with the same average power, we can see that UWB signals contain significant amount of residual voltage after overcoming the diode drop in a

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[4] (This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract, DE-AC52-07NA27344-LLNL-PRES-401,143)

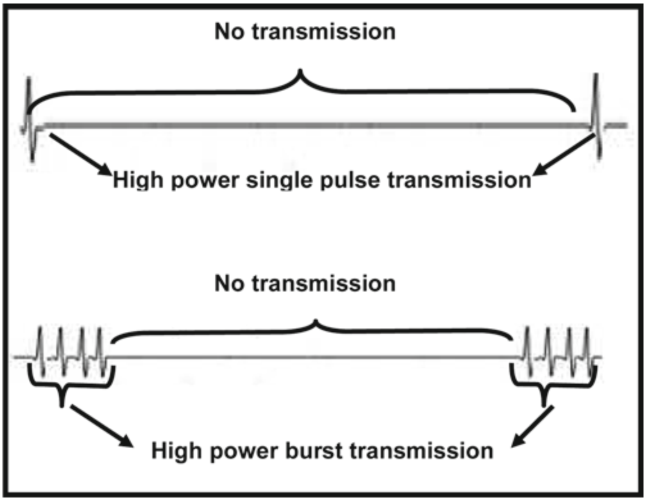

Fig. 3.9 Low duty cycle in UWB transmission; (*top*) single pulse transmission (*bottom*) burst transmission

remote electronic circuit. This is due to their high peak power and low duty cycle that provides enough instantaneous power to compensate for the diode drop while still maintaining the low average power. Figure 3.10 compares the ability of narrowband and UWB signals for their remote powering capability.

As shown in Fig. 3.9, after overcoming the diode drop (usually 0.7 V), narrowband signals do not have enough power left to remotely power any electronics circuit from a far distance. However, for the same average power, UWB signals are capable of powering electronic circuits from a far distance even after compensating for the voltage used in diode drop.

Figure 3.11 shows that a typical transmitted UWB pulse for remote powering experiments has 1 KV peak-to-peak amplitude for the duration of only 12 ns. The received signal at 15 m distance has peak amplitude of 3 V which translates to 180 mW of peak power. This experimental result shows that a passive UWB tag can be remotely charged at a much longer distance with a reasonable duty cycle since only microwatts of average power is required to power up passive tags; (for minimum identification capability, tags with memory need more power). It's important to mention that antenna design plays an essential role in the remote powering range; high-gain, directional multi-element antennas, provide remote powering capability at longer distances. Furthermore, changing the diodes in passive tags to Schottky diode can increase the remote powering distance further. Schottky diodes have the advantage of low forward voltage drop across their terminals (approximately 0.15 – 0.45 V) compared to normal diodes that have a voltage drop of 0.7 – 1.7 V. The decreased voltage drop provides high efficiency in remote powering of tags and adds to the remote powering distance [14].

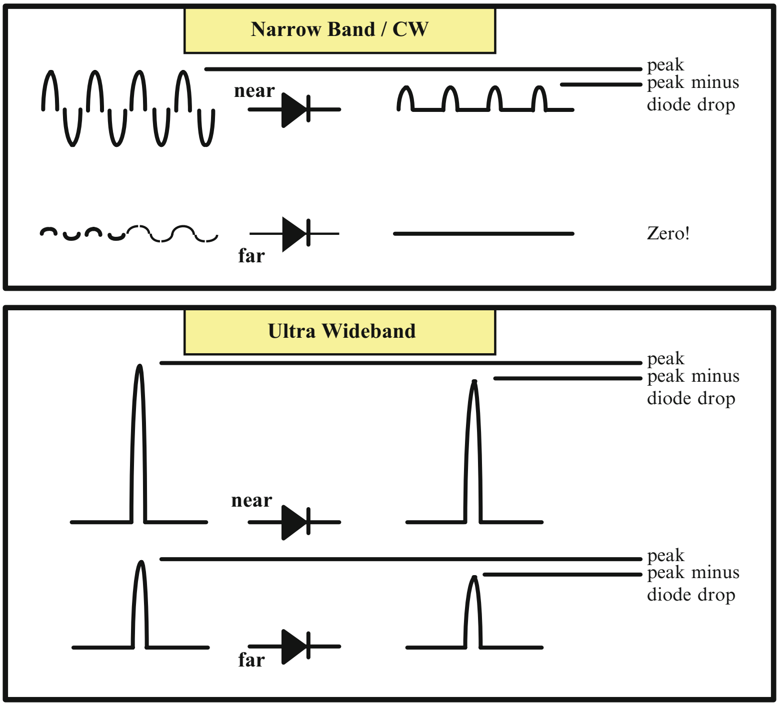

Fig. 3.10 Continuous wave narrowband signals (*top*) can power up electronic circuits in a short distance. For the same average power, UWB high power, low duty cycle signal (*bottom*) contains enough energy to power up a device from a far distance[5]

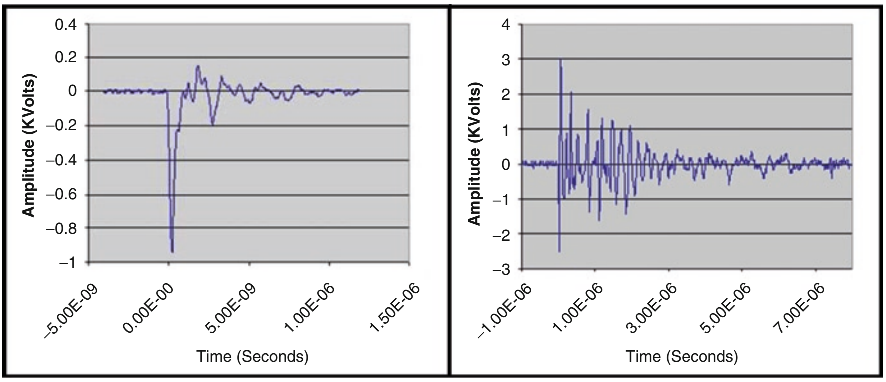

Fig. 3.11 Actual transmission of a UWB signal and the actual voltage available in a remotely powered circuit from a distance of 15 m[5]

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[5] (This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract, DE-AC52-07NA27344-LLNL-PRES-401,143)

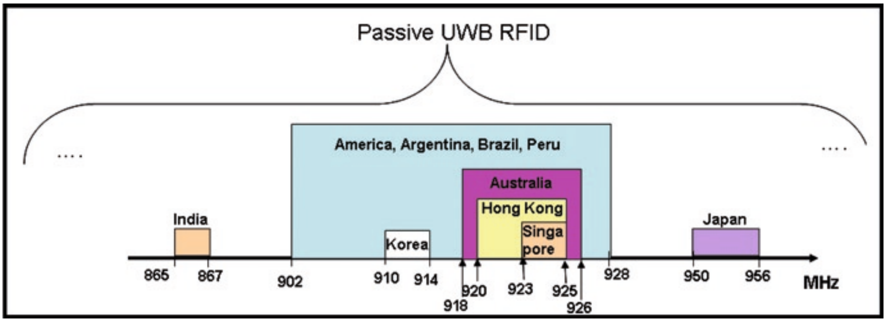

Fig. 3.12 Regulatory specifications for UHF passive tags in various countries versus passive UWB RFID's freedom to operate around the world

3.2.8 Global Solution Due to Operation in Unlicensed Spectrum

UWB RFID systems operate over a wide band of frequency spectrum at FCC's power limit of −41.3 dBm/MHz (75 n-Watts/MHz)[6] . The low power spectral density allows UWB RFIDs to co-exist with legacy radio services and operate over a large portion of the frequency spectrum. Therefore, the local restriction of use on certain frequency bands in a specific region of the world does not limit the operation of UWB RFIDs. These systems can be developed for use in applications that are not limited to any country and can be used worldwide. As will be discussed in Chap. 4, passive UWB tags do not have any FCC limitations in power and frequency band and can use a large portion of the spectrum with-out the need for licensing. Therefore, they can address the limitations of UHF passive tags in various parts of the world. Figure 3.12 illustrates the frequency restrictions of UHF passive tags in the unlicensed spectrum worldwide, and how UWB passive RFID tags can be used globally without any frequency restriction.

The Fig. 3.12 shows the advantage of passive UWB RFIDs over narrowband UHF tags since they can be used all around the world with no restriction in their operating frequency [15, 16].

The active and semi-active UWB RFID systems are considered as UWB communications system and should follow the FCC regulations. Although FCC limits the use of commercial UWB communications (active/semi-active tag/readers, and passive/semi-passive readers) systems to 3.1–10.6 GHz, still 7.5 GHz of unlicensed spectrum is available to UWB RFIDs to coexist with legacy radio services Fig. 3.13.

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[6] (This limit applies to UWB transmissions in Europe (ETSI), Japan, Korea, Singapore, etc.)

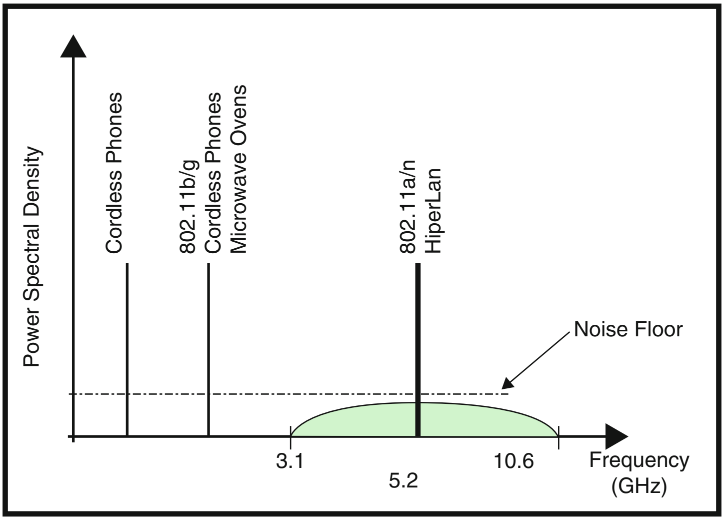

Fig. 3.13 Co-existence of UWB signals with narrowband and wideband signals in the RF spectrum

3.2.9 *Small Form Factor and Low Cost Tags*

As mentioned earlier in Chap. 2, UWB carrierless (baseband) transmissions have simpler circuitry and need fewer RF components than the narrowband carrier based transmissions. This is because low power UWB baseband signals do not need any power amplifiers (PA), mixers and local oscillators for IF filtering and heterodyning. In addition, the UWB baseband pulses are analog signals and there is no need for analog-to-digital converters (ADC). Figure 3.14 illustrates the simplicity of UWB RFID systems RF frontend circuitry as compared to narrowband RF transceivers.

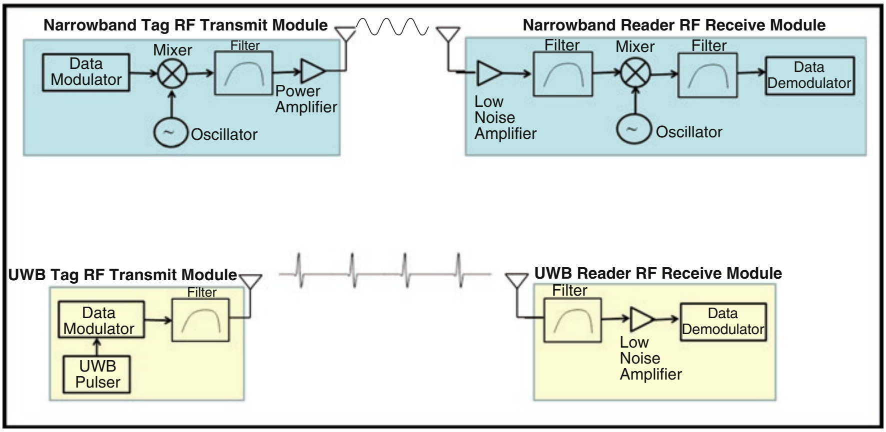

Fig. 3.14 RF circuitry for (*top*) narrowband RFID systems (*bottom*) UWB RFID systems

As shown in Fig. 3.14, UWB RFIDs have considerably simpler architecture compared to their narrowband counterparts. This simple architecture allows the transceiver circuit of UWB RFID active tags and readers to be implemented in CMOS technology with small form factor and low production cost. Furthermore, as discussed earlier, RFID tags do not need the additional digital cryptography unit due to their physical layer security for pulse modulation that makes them far simpler than narrowband RF tags.

3.3 UWB Modulation Schemes for RFID

There are a number of pulse modulation schemes that can be used in UWB RFIDs. Some modulation techniques such as on-off keying (OOK) and pulse amplitude modulation (PAM) are suitable for passive tags due to their simplicity of implementation; however they can be used in active RFID systems also. On the other hand, UWB modulation schemes such as pulse position modulation (PPM) or time hopping pulse position modulation (TH-PPM) are more complicated in implementation due to their strict synchronization requirements. These modulation schemes are appropriate for active tags and offer a level of security at physical layer that can eliminate the need for power consuming higher-level digital encryption. Transmitted-reference (TR) modulation technique has less restriction on its synchronization requirements compared to the two former pulse modulation systems, so it could be used for active UWB tags with simpler architecture. The concept of TR modulation can also be used for passive UWB tags by using time-reversal technique.

It's important to emphasize that the goal for a successful RFID system design (passive or active) is to design low complexity tags to save power, cost, and size while moving the complexity to the reader side. The reason is that the number of readers used in any application is much lower than the number of tags. In this chapter, we cover the above mentioned UWB modulation schemes in detail and discuss how each one can benefit RFID systems.

3.3.1 On-Off-Keying (OOK) : Pulse Presence or Absence

On-off-keying is the simplest form of UWB modulation where presence of a pulse corresponds to a transmitted data bit "1" and the absence of a pulse represents a transmitted data bit "0" as shown in Fig. 3.15.

OOK modulated signal can be represented by a general signal model defined in the following Equation:

$$s(t) = \sum_{m=1}^{M} b_m \cdot P(t - mT) \tag{3.2}$$

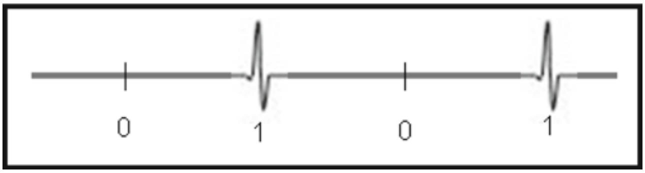

Fig. 3.15 Example of on off keying (OOK) UWB modulation

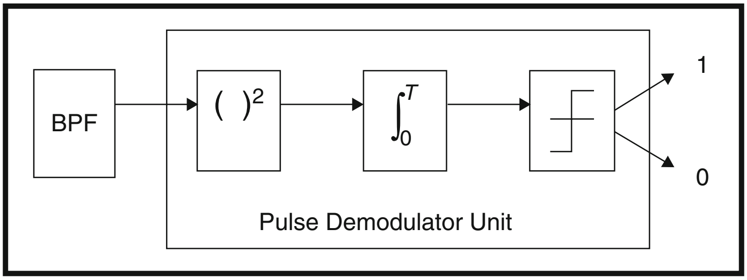

Fig. 3.16 Block diagram of a non-coherent energy detection receiver used in OOK UWB active and passive readers (refer to Figure 3.5)

In this equation, M depicts the maximum number of transmitted bits, $P(t)$ represents the transmitted UWB pulse, the m^{th} data bit is represented by $b_m \in [0,1]$, and T is the pulse repetition period.

OOK is a simple version of Pulse Amplitude Modulation (PAM), which will be discussed in the next subsection. OOK modulation can be implemented by a simple switch that can turn an RF tag on or off. This simplicity allows active UWB RFID tags to save power and have extended battery life since their transmitter can stay off for the periods of time that it is transmitting “0”. With such low power consumption, OOK allows a great deal of retransmissions for active tags. OOK can also be used in passive tags to modulate the backscattered signals in UWB RF tags.

The OOK reader can detect the backscattered signals or the actively transmitted signals by a simple *non-coherent energy detection impulse radio receiver*[7] circuit as shown in Fig. 3.16.

The low complexity of OOK modulation scheme is highly desirable in UWB RFID implementation; however this technique is sensitive to intentional and unintentional interference, since an interfering signal can easily be detected as a

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[7] (Energy detector receivers calculate the signal energy by squaring the received signal. If the detected energy passes a predefined threshold level, the data is demodulated as a digital bit “1”. If the data is not present or its energy does not pass the threshold level, the received data will be demodulated as “0”.)

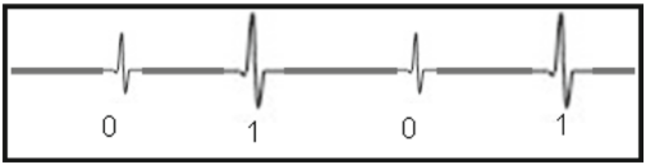

Fig. 3.17 Representation of pulse amplitude modulation (PAM)

false data bit. Therefore, high signal to noise ratio (SNR) is required for reliable detection, where it can be achieved by shorter distances or more complex readers with interference mitigation techniques such as pulse averaging. Also multi-tag detection in both passive and active tags is challenging using OOK since interfering signals can create false alarms in tag detection.

3.3.2 Pulse Amplitude Modulation (PAM) : Pulse Strength

In pulse amplitude modulation data bits are encoded by the strength of UWB pulses where stronger pulses represent 1’s and weaker pulses represent 0’s as shown in Fig. 3.17.

PAM signals can be defined the following general signal model:

$$s(t) = \sum_{m=1}^{M} A_{b,m} \cdot P(t - mT) \tag{3.3}$$

where the amplitude or power level for each user’s data bits is represented by $A_{b,m}$, M shows the maximum number of transmitted bits, the UWB pulse is $P(t)$, $b_m \in [0,1]$ depicts the m^{th} data bit, and the pulse repetition period is represented by T. As shown in the above (3.3), the signal models for PAM and OOK techniques are similar, except for the presence of the amplitude parameter, $A_{b,m}$, in PAM model.

Similar to OOK, UWB PAM technique is a useful modulation scheme for both active and passive tags. In the passive case, the tag RCS varies based on tag antenna’s impedance matching between two states that represent the pulse amplitude. UWB RFID readers can detect PAM signals from passive or active tags using a simple non-coherent energy detector (shown in Fig. 3.16) to keep their complexity low. Compared to OOK, PAM is less vulnerable to interference from external signals, however, interference mitigating techniques in the reader could improve the overall performance of a pulse amplitude modulated UWB RFID systems.

3.3.3 Pulse Position Modulation (PPM) : Pulse Location

Pulse position modulation is a powerful technique for "active" UWB tag implementation. In this modulation scheme, the exact position of transmitted UWB pulses is used for encoding data. There are many variations and implementations for modulating pulses based on their position, however, the common idea behind all of them is the relative position of two pulses with respect to a reference point in time. One version of PPM shown in Fig. 3.18 pseudo randomly encodes a UWB pulse by digital data "0" and "1" by positioning the pulses before and after a reference point with a certain shift in time (δ). The interval between the reference point and the pulses can be randomly selected from a predefined window to avoid collision between multiple tags simultaneously sending their data.

The PPM modulated signals can be modeled by the following Equation:

$$s(t) = \sum_{m=1}^{M} P\left(t - mT + b_m \delta\right) \tag{3.4}$$

Similar to the previous equations the maximum number of transmitted bits is represented by M, $P(t)$ is the UWB pulse, $b_m \in [-1,1]$ represents the m^{th} data bit, T is the pulse repetition period, and δ represents the modulation index that provides a time shift for the position of digital bits with respect to the reference point.

As shown in the above Equation and Fig. 3.18, UWB pulses used in PPM have the same amplitude and polarity, therefore, they are more immune to false detection due to noise and interference compared to OOK and PAM.

The PPM UWB tags can be detected and uniquely distinguished from each other by *template matching techniques*[8] performed at their associated UWB reader, shown in Fig. 3.19.

The PPM demodulation is a complex process due to its stringent synchronization requirement between the transmitted and received bits. Therefore, this technique is only suitable for active RFID systems where enough power is available to tags for both

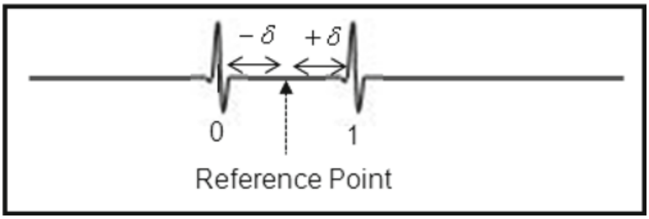

Fig. 3.18 Example of pulse position modulation (PPM)

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[8] (Template matching techniques correlate the received signal, comprising of the transmitted signal and channel noise, with a pre-defined template (similar to the transmitted signal) to maximize the received signal's SNR and detects the desired signal from the background random noise.)

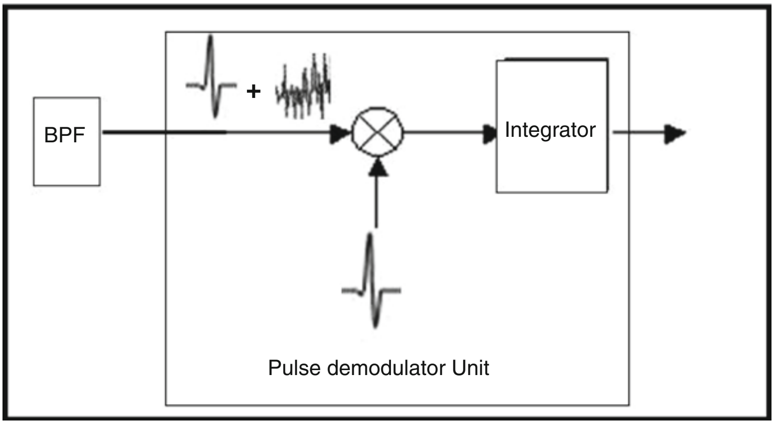

Fig. 3.19 Block diagram of a template matching receiver used in PPM UWB active readers (refer to Figure 3.5)

transmission and reception. An extension to PPM techniques is called Time Hopping PPM (TH-PPM) where each bit follows a specific time hopping sequence [3]. This technique has been reported in literature for active UWB RFID implementation with highly secure physical layer [8].

3.3.4 Bi-phase Modulation : Pulse Polarity

In bi-phase modulation technique, UWB pulses represent digital data bits by changing their polarity as illustrated in Fig. 3.20.

The change in polarity in Bi-phase modulated signals makes them less prone to channel distortions since the difference between two pulse levels is twice each pulse's amplitude. The bi-phase modulated UWB signals and can be generally modeled by the following Equation:

$$s(t)=\sum_{m=1}^{M} b_m P(t-mT) \tag{3.5}$$

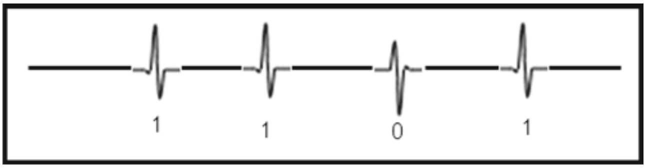

Fig. 3.20 Example of Bi-phase modulation

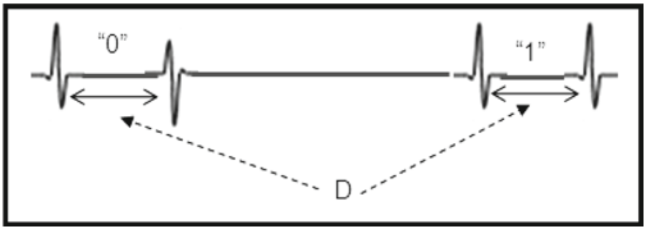

Fig. 3.21 Example of TR pulse modulation

In the above Equation, M is the maximum number of transmitted bits, $P(t)$ is the UWB pulse, $b_m \in [-1,1]$ represents the m^{th} data bit, and T is the pulse repetition period.

Bi-phase modulated pulses generate a smooth spectrum due to the change in their polarity, so they are less interfering with other radio systems and with each other. This scheme is particularly useful for UWB RFID systems when a large number of tags need to communicate with one reader without cross interference.

Bi-phase modulated pulses can be detected and distinguished from each other using both the energy detection and template matching demodulation units in the readers (shown in Figs. 3.16 and 3.19) receiver circuits. Although in most RFID systems, the reader has a more complex architecture than the tag, in this case the tag might need to be more complicated to implement due generation of both positive and negative pulses. In addition, accurate timing and synchronization between the two transmitters is crucial to the functionality of such systems, therefore, this technique is only suitable for active tags.

3.3.5 Transmitted-Reference Modulation : Pulse Delay

In the conventional form of transmitted-reference (TR) modulation, a UWB doublet with a unique delay between its two pulses represents a data bit. The first pulse in the doublet is not modulated and acts as a "reference" for the polarity modulated second pulse that carries data. The delay, D, between the two pulses is unique to each channel tag and is known to the demodulator at the reader. Figure 3.21 represents an example of UWB TR modulation technique.

Transmitted-reference modulation is mathematically represented by the following Equation .

$$s(t) = \sum_{m=1}^{M} [P(t-(m-1)T) + (2b_m - 1)P(t-(m-1)T - D)] \tag{3.6}$$

Similar to the previous equations M is the maximum number of transmitted bits, $P(t)$ represents the UWB pulse, $b_m \in [0,1].$ is the m^{th} data bit, and T is the symbol (doublet) repetition period, and D represents the unique delay between the pulses in TR doublets.

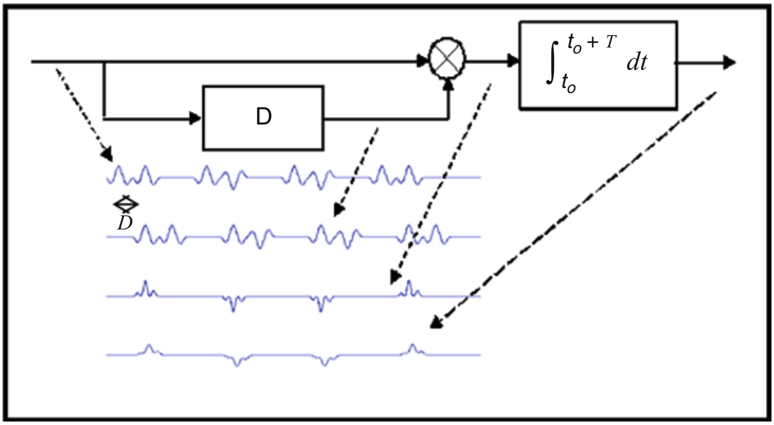

Fig. 3.22 Block diagram of a TR receiver[9]

Unlike conventional pulse matched filters, TR receivers work based on correlating the received signal with its delayed replica as shown in Fig. 3.22.

As shown in Fig. 3.22, The delay will cause the reference pulse to act as a template for data pulse in correlation process. TR receivers are more effective than the conventional matched filters for detecting narrow UWB pulses, since channel distortion has the same effect on the input signal and the template (reference pulse). Hence, unlike PPM receivers, in multipath channels the stretch to UWB pulses will not degrade the detection capability provided that the delay spread is not larger than *D*. Figure 3.23 illustrates an example of a TR modulated signal in a reflective multipath environment.

Another advantage of TR modulation is relaxing the synchronization requirement due to the fact that the receiver has a prior knowledge of the delay between pulses and sampling occurs after the correlation. Therefore, the need for a fast analog-to-digital converter (ADC) is eliminated in TR receivers. Despite all the advantages of TR modulation technique over other UWB pulse modulations, the noise-on-noise interference on the received signal can be a drawback of the method. However, additional interference mitigation techniques are available to address this problem [17, 18].

The TR modulation technique is suitable for active and semi-active RFID systems that are used in harsh RF propagation environments including metallic assets. Moreover, TR modulated RFID readers have simple architecture due to the relaxed synchronization features.

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[9] (This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract, DE-AC52-07NA27344-LLNL-PRES-401,143)

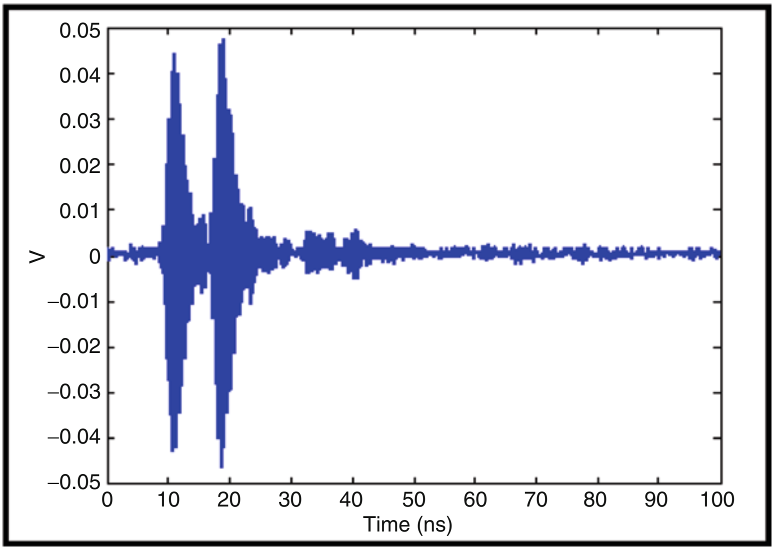

Fig. 3.23 Representation of TR modulated signals in a multipath channel[10]

3.3.6 Time-Reversal Modulation : Pulse Matching

Time-Reversal modulation is a powerful technique for reconstructing signals from a UWB RFID tag in cluttered environments. This modulation technique is similar to transmitted-reference modulation in terms of resolving multipath, however, the advantage of time-reversal method is that it can be used for passive tags also. In passive UWB RFID systems, the reader sends two pulses with a known delay in time and detects the backscattered delayed pulses using pulse compression. Time Reversal is similar but somewhat different from matched filtering that is used heavily in conventional pulse detection systems. In this method of communications, both the channel and the signal are matched instead of just the shape of the transmitted signal [19–22]. The backscattered signals from a passive UWB RFID systems can be reconstructed by *retracing* all of the multiple paths that originally distorted the transmitted signals. The time-reversal reader uses its knowledge of the medium (channel response) to superpose them together to their signal levels and detectability as shown in Fig. 3.24.

In Fig. 3.24, $s(t)$ represents the transmitted UWB pulses transmitted with a delay of τ in time, $r(t)$ and $h(t)$ depict the received signal, and the channel response respectively, $n(t)$ represents the channel noise. As shown in the reverse link, the cross cor-

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[10] (This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract, DE-AC52-07NA27344-LLNL-PRES-401,143)

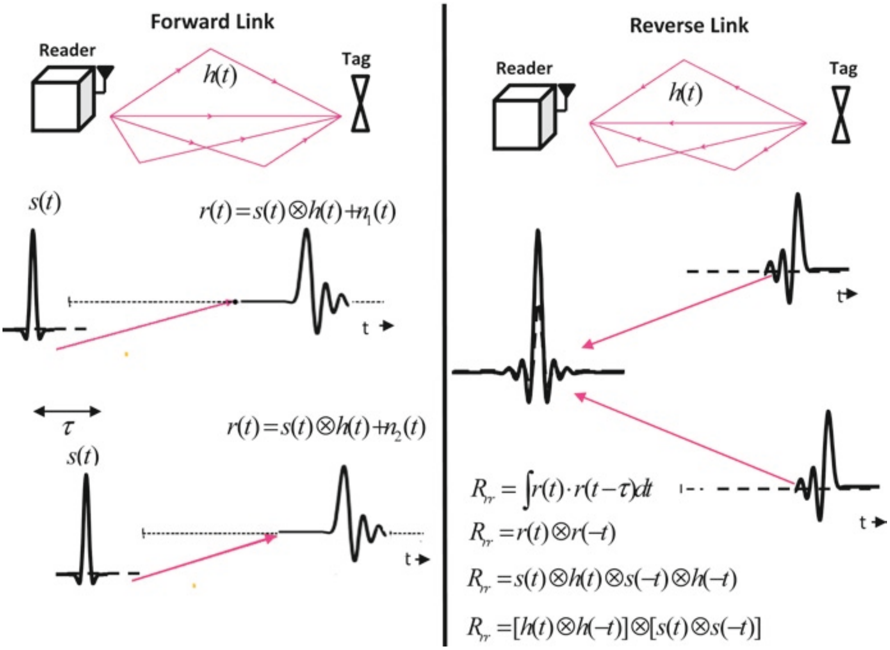

Fig. 3.24 Passive UWB RFID system with time-reversal modulation in forward and reverse links[11]

relation of the received signal and its delayed version, R_{rr}, generates a strong profile for the return pulse from a tag by compressing the pulse at the reader.

Time-reversal is an effective method in communication because it attempts to compensate for the phase distortions that occur in cluttered propagation media [23–25]. Going back to the notion of transmitted-reference signaling, the tag reader can send a signal and its time reversed form to recover from propagation distortions. Since the reader in in RF tag system is sending and receiving the backscattered pulses, implementation of time-reversed communication in a RF tagging system is rich area of research and development for advanced signaling concepts. Orthogonal coding by passive tags on the backscattered signals offers additional level of modulation to time-reversal for more resilience to channel noise. In this approach, the passive tag reflects a signal with a predefined code (known to the reader) and shapes the reflected signal. The time-reversal reader detects and recovers the received code and identifies the unique tag ID by correlating the received code with the bank of tag codes stored in its memory. It's important to note that for unique identification of multiple tags, the tag codes need to be orthogonal to each other. Figure 3.25 illustrates an example of the orthogonal coding for passive UWB RFID systems with time-reversal modulation.

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[11] (This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract, DE-AC52-07NA27344-LLNL-PRES-401,143)
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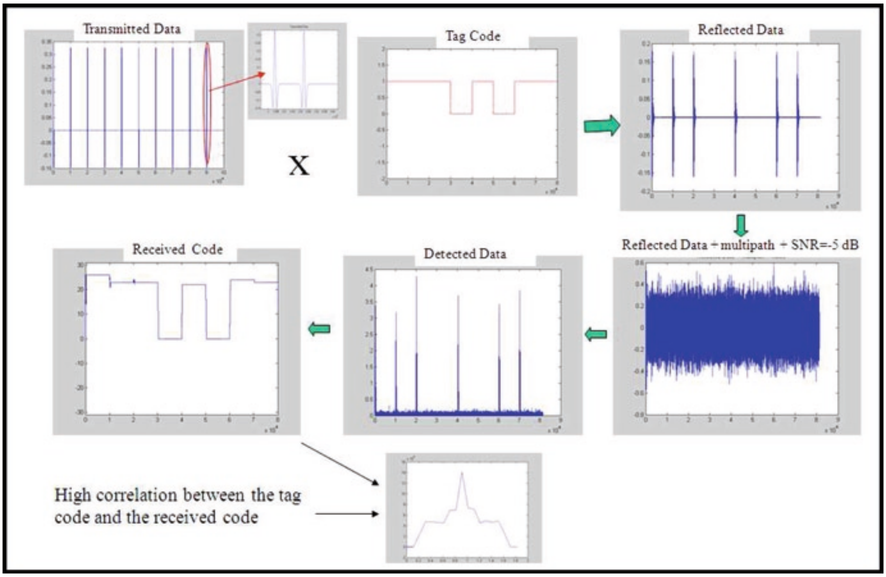

Fig. 3.25 Passive tags can shape the reflected signals using orthogonal coding for multiple tag detection purpose in time-reversal modulation[12]

3.4 Performance Evaluation Of Commercial UWB RFID Systems

Shortly after the approval of unlicensed UWB transmission for commercial applications by the Federal Communications Commission (FCC) in February of 2002, active UWB RFID systems by companies such as Multispectral Solutions Inc., Time Domain Inc., and Ubisense Ltd. appeared on the market. These products have been successful in solving some of the shortcomings of active narrowband RFID systems through the use of UWB signaling.

In this section we present the results of performance benchmarking of the state-of-the-art commercial "active" UWB RFID systems for their possible use in various applications. Particularly, this section examines the performance and benchmarks two of the state-of-the-art commercially-off-the-shelf (COTS) active UWB RFID systems developed by Multispectral Solutions, Inc. (Zebra Enterprise Solutions) and Ubisense, Ltd.

The results presented here are based on recent benchmark studies with additional feedback from the vendors. These results are preliminary and do not imply a comparison between the ultimate utility of the systems under evaluation. The benchmark studies

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[12] (This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract, DE-AC52-07NA27344-LLNL-PRES-401,143)

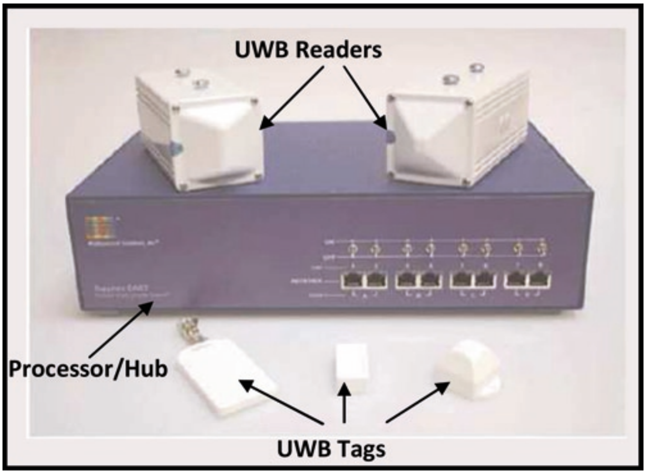

Fig. 3.26 Hardware components of MSSI Sapphire DART system

are comprised of various application scenarios required for a successful tracking system including:

- Long range detection
- Positioning accuracy
- Functionality in the presence of metallic objects
- Functionality in the presence of liquids

This benchmarking involved both indoor and outdoor tests to set limits on the practical scenarios for a true real time tracking and positioning evaluation for each of the systems. It must be emphasized that the purpose of benchmarking is not to compare the two systems; it is to understand the unique capabilities of the MSSI and Ubisense systems and establish an application space where their complementary features might be useful. The details about each of the two systems under evaluation are given below to facilitate familiarity.

3.4.1 MSSI RTL System

The MSSI RTL system is called the "Sapphire DART" and includes the following components:

1. RFID tags,
2. RFID Readers,
3. Processing hub to provide power and synchronize readers with connecting cables, and
4. Embedded software for system configurations and graphical user interface (GUI) to display the real-time location of tags and readers Fig. 3.26.

3.4.2 Ubisense RTL System

The Ubisense Real Time Location system consists of the following components:

1. Ubisense tag (including an LED for easy recognition, a sensor for activating a immobile tag, and a button to trigger events),
2. Ubisense sensor (reader),
3. Power over Ethernet switch, and
4. Embedded software for system configurations and GUI for presenting the real-time 3-D location of the tags and sensors Fig. 3.27.

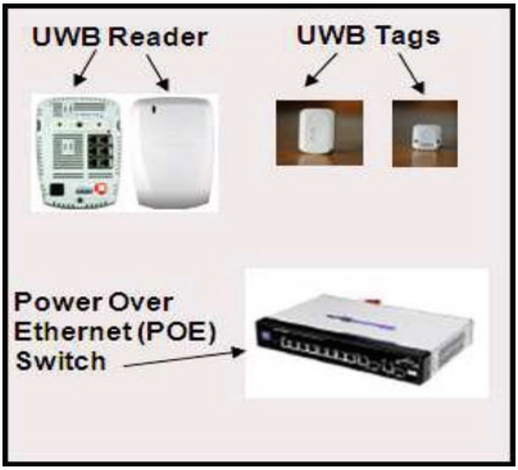

Fig. 3.27 Hardware components of Ubisense RTL System

Both the MSSI and Ubisense readers only require power from the CAT5 cables through the hub. Given that the UWB systems have relatively simple transceiver architecture, these systems provide tags and readers with a compact form factor; making them portable and easy to deploy.

3.4.3 Performance Benchmark Experiments

The performance characteristics of these systems were evaluated under the same conditions. The discussion of the tests begins with details of the experimental set up, the parameters that were controlled, and measurement procedure followed by the test results. It's important to emphasize that the results presented here are based on a limited test case and as with any RF system evaluation, the results may vary based on the exact setup which depends on many parameters including but not limited to:

- Antenna height from the ground
- Radio propagation environment
- The surface to where the tag is attached
- Thresholding options for signal detection

Fig. 3.28 Picture of the outdoor test environment. The straight length of the corridor measures 600 ft

3.4.3.1 Test I: Long Range Detection

Detection range plays an important role for various remote monitoring applications where the ultimate goal is to track the location of objects of interest inside buildings, in between buildings in a facility, and eventually be able to track them in transport. The latter task cannot be accomplished with one RFID system and needs a combination of RFIDs and regional navigation systems.

The first test involved the maximum detection range of both UWB RFID systems in an outdoor environment. One reader was situated outside at one end of a pathway that separated two three-story buildings (shown in Fig. 3.28). The reader was placed on a 5 ft high platform and the tag (not attached to any object) was moved directly and continuously away from the reader until the detection of the tag was not observed.

Experimental Results

In this experiment, real-time graphical information was used to identify the tag-under-test in both systems. The detected range for MSSI and Ubisense systems were about 351 ft and 210 ft respectively. Signal degradation started to begin at about 300 ft for MSSI system with a refresh rate of 2–5 s[13]. Same signal degradation occurred for Ubisense system at about 175 ft with a refresh rate of 4–7 s Fig. 3.29.

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[13] (A discussion with the vendor about range limitation revealed that in our experiments we used the mid-gain antenna which is one of the three antennas offered with Sapphire DART receivers. According to the vendors engineering team, with additional training on antenna planning, distances can improve the performance on a case by case basis.)

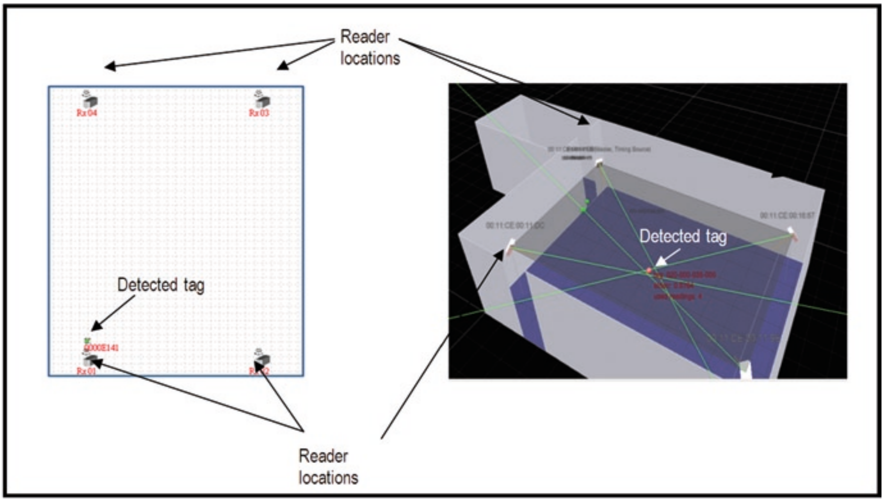


Fig. 3.29 Examples of the graphical user interface for both systems, (*Left*) MSSI, (*Right*) Ubisense

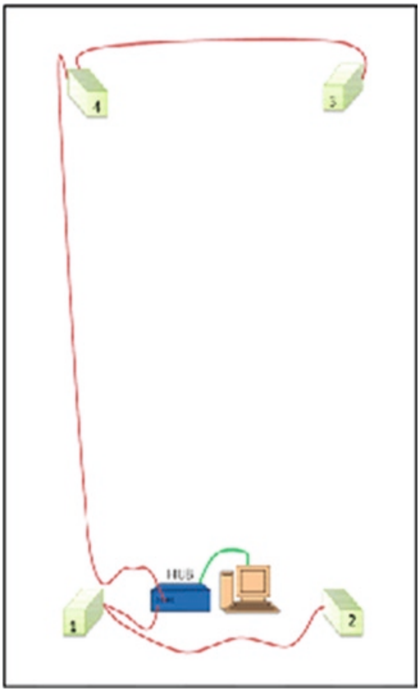
It is important to emphasize that the MSSI system is not limited to providing data only in graphical representation, even though that is the manner in which the data were validated in this portion of the evaluation. In addition to the real-time demo used in this experiment, the embedded software used by the DART systems offer several other diagnostic tools that include:

- Filtering of the raw output data by tag and data type,
- Enabling a diagnostic packet feature,
- Enabling the P-data which helps the user assess why location data is not available for a particular tag event,
- Receiver test feature in the diagnostic tab which allows for analyzing tag detection.

3.4.3.2 Test II: Real Time Location (RTL) Accuracy

Accurate location of assets is highly desirable to many inventory and chain of custody applications. Locating a tagged item requires multiple readers to detect the tag signal and triangulate the tag position based on received signal strength (RSS), time-of-arrival (TOA), differential-time-of-arrival (DTOA), or angle-of-arrival (AOA) information. The physical nature of narrow UWB pulses in RTL systems brings an inherent advantage to accurate positioning, given that a 1 ns pulse directly translates to 1 ft spatial resolution. It is important to note that additional signal processing and filtering can be applied to UWB RTL systems, in order to increase the accuracy of tag location. This test evaluated the accuracy of locating objects using MSSI Sapphire DART and Ubisense RTL systems. Our measurement involved

Fig. 3.30 The Star Configuration. Only two readers are directly connected to the hub while the other two are daisy chained to the first two



four readers with a specific configuration, called “Star Configuration” (shown in Fig. 3.30). Star configuration was implemented to maximize efficiency with respect to the logistical setup of the readers and the hub.

The position evaluation emulated an indoor environment with a relatively harsh RF propagation channel. Four readers were placed in the corners of a room measuring 20 by 35 ft with a 10 ft high ceiling. The room was populated with metallic cabinets, desks, two metallic containers, and lab equipment. The readers were placed on a 7 ft platform and the tags under scrutiny were placed in random spots throughout the room where their positions were displayed by the GUI on each system. Tag positions detected by GUI were verified by their actual positions in the room.

Experimental Results

The indoor tag location test proved to be successful; all of the tags were detected with a position resolution of 1–2 ft for MSSI system and 0.5–1 ft for Ubisense. This means that the position of the tag determined by the readers deviates from the actual position of the tag. The only instance when a tag was not located properly occurred when the tag was placed outside of the plane defined by the readers. The results of this experiment indicted the importance of the accurate coordinates as an input parameter for both systems. Discussions with the MSSI on location accuracy results revealed that the GUI uses raw output data and is not the best method for evaluating the accuracy of the tag position. Other options, for example, statistical analysis of the reader data are available to provide more accurate location of tags[14].

3.4.3.3 Test III: Tag on Metal

In most inventory applications, assets are either a metallic construct or reside on metallic shelves. Propagation of narrowband CW radio signals in the presence of metallic objects is vulnerable to reflection, multipath interference, and antenna coupling. UWB signaling, because of frequency diversity, is less vulnerable to the above mentioned problems. In order to test this hypothesis the two systems under investigation were evaluated in the following scenarios:

1. Tag detection and location on a metallic object
2. Tag wrapped in metal (aluminum foil)

The second scenario relates to shielding attacks discussed in Sect. 2.2.1.

3.4.3.4 Part One: Tag Detection and Location on Metallic Object

The metallic objects used for this experiment was an empty metallic container measuring 2.5 by 3 ft, shown in Fig. 3.31. The tag was simply placed on the face of the container while readers remained distant, detecting and locating the tag. Similar to Test I and Test II, the readers where placed on a 5 ft high platform for detection test and 7 ft high platforms for positioning test.

Experimental Results

In both systems, the UWB tag was detected and located as if no metallic object was present and the same signal integrity was achieved in locating a tag on a metallic and non-metallic object.

The accuracy of locating the tag was 1–2 ft for MSSI system and 0.5–1 ft for Ubisense system, just like the results achieved form the experiment on non-metallic objects. Similar to Test II, in this experiment, graphical representation was used for locating the tags.

3.4.3.5 Part Two: Tag Wrapped in Foil

This test illustrates one of the major advantages of pulsed UWB signals. When a tag is wrapped in aluminum foil, small gaps and openings allow the signal to propagate

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[14] (According to the vendor "Tag to receiver line of sight ensures the most accurate TDOA position calculation so any condition that limits this physical configuration will degrade the accuracy of the position calculation but inaccurate coordinate data for the receiver infrastructure and reference tag may contribute as well".)

Fig. 3.31 UWB tag on metallic container

as described earlier in Sect. 3.2.4. One hypothesis is that the cracks and openings could act as waveguides to help UWB signals propagate outside. In order to evaluate this hypothesis a UWB tag was wrapped in a small sheet of aluminum foil to investigate if the signal could be detected.

Experimental Results

The foil test produced impressive results for both systems. The signal was detected but with a short delay of 1–4 s of initial signal acquisition. The reason for this delay is not intuitively obvious; however, it may have been caused by some variable in the configuration or the manner in which the data was being monitored.

It is important to emphasize that in both cases the fact that tags were detected from inside a foil wrap is rather impressive and shows a unique capability of UWB signaling versus narrowband signaling in RFIDs.

3.4.3.6 Test IV: Tag on Liquid Container

One theoretical limit with respect to high frequency communications is the poor permeability of the wave or pulse through absorptive materials, such as water.

Fig. 3.32 Experimental setup for tag on liquid container

In this test case, the performance of both UWB RFID systems are evaluated with the tags attached to a large water container as shown in Fig. 3.32.

To ensure that a signal was being received through the water and not around it, the personnel tag from each vendor was employed. This tag is intended to track human assets and takes the form of a badge. Because the badge may flip about while attached to clothing, a plate antenna has been placed on both the front and back sides of the tag to ensure detection.

3.4.3.7 Tag Detection and location on Liquid Asset

The detection test was performed based on the same criteria as previous benchmark range and location tests. The tag moved directly away from a stationary reader until detection and location capabilities were ceased. The range test was performed outdoors and the location test was performed indoors. In this setting the tag was attached to the water container with the back of the tag facing the reader in the range test, as seen in Fig. 3.33. However, for the location test, both sides of the plate antenna were exposed due to the tag being surrounded by the readers.

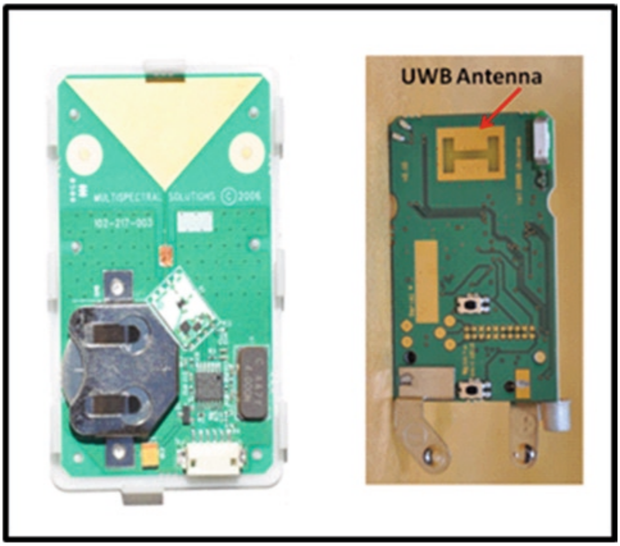

Fig. 3.33 UWB Personnel Tags (*Left*) MSSI, (*Right*) Ubisense

Experimental Results

As discussed earlier the tag performance is reduced when the RF signal is confronted with absorptive materials. Our practical tests indicate that the effective maximum range and location resolution of a tag while attached to the water container at a range of 118 ft was about 4–6 ft of location accuracy, and at a range of 52 ft, a 3 ft location accuracy, for the MSSI and Ubisense systems, respectively.

3.4.4 Concluding Remarks[15]

The limited tests that we performed demonstrated successful performance of UWB tags for both MSSI Sapphire DART and Ubisense RTLS systems. Each of these

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[15] (This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, LLNL-TR-433,473.

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systems demonstrated the advantages of using UWB signaling for detecting and locating distant long-range objects with a fine spatial resolution, especially on conductive materials. The impressive results for both systems were their capability to be detected and located with high accuracy on metallic objects.

The range test in metallic objects generated a resultant effective range of 351 ft for the MSSI system and 210 ft for the Ubisense system. These systems would be useful for several scenarios including inventory control where the detection of presence and absence of metallic items (or items stored on metallic racks) with unique identification is required.

Tag location accuracy for the indoor plane with a small location area was successful in both systems. Location accuracy only deviated from 1 to 2 ft for the MSSI system, and 0.5–1 ft for the Ubisense system. This level of deviation may be considered negligible for larger facilities. A discussion with the vendors indicated that the deviation could be reduced with accurate mapping of the coordinates as well as using additional features in their software. However, after comparing the UWB with narrowband RTLS RFID systems, the level of geolocation accuracy in positioning of UWB tags is impressive.

The performance of commercial UWB active RTLS systems indicate that they can provide an intermediate solution to the various inventory and chain of custody processes. However, realistic chain of custody applications may require longer ranges, and none of the commercial UWB RFID systems to date can provide the long range requirements in chain of custody applications. Based on the experience with the state-of-the-art commercial UWB RTLS systems we believe that custom designed solutions that offer the advantages of UWB signaling and provide longer detection links with wireless readers, is the ultimate solution for many chain of custody applications.

3.5 Summary

Ultra-wideband technology brings significant advantages to wireless communications and radar systems by addressing the operational challenges of narrowband RF signaling schemes. In this chapter, we addressed the shortcomings of traditional RFID systems that were described in Chap. 2, focusing on the use of UWB signaling for RFIDs. The challenges addressed in this chapter included: performance on or around metallic objects, privacy and security concerns related to the ability to detect RFID signals by adversaries, signal fading and blockage, high power requirement of active tags and their limited lifetime, inadequate range of passive tags, and last but not least, limitations to worldwide operations. In order to support our expectations on improving RFID operations through UWB signaling, we presented performance benchmarking results based on some limited test cases on two state-of-the-art active UWB RFID systems from MultriSpectral Solutions Inc. and Ubisense Ltd. The results from the limited sets of experiments in our benchmarking study clearly revealed the advantages of using UWB technology for RFID systems to tackle some of the existing challenges such as position accuracy and performance around metallic objects. Despite this level of success for both of the devices under test, after a discussion about these results with the vendors, we realized that some of the evaluations were not based on the optimal software and hardware configuration for such systems and more testing might be required to understand the ultimate capabilities of these systems.

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Chapter 4
Ultra-Wideband Technology for RF Tags: Concepts, Implementations, and Regulations

4.1 Introduction

UWB RF tag is an important technology for non-LOS identification of objects in harsh EM environments. Currently, there is a significant degree of activity in the UWB RF research community to develop UWB tags with robust operational characteristics, features not available with other conventional RF tags. While UWB tag technology is still at an early stage of development and its full potential is yet to be realized, as discussed in Chap. 3, early versions of *active* UWB tags are now available in the market. Performance of active UWB tags with respect to tag *geolocation* accuracy is quite impressive. In many instances UWB tags can be localized to within few centimeters of their actual positions. Some research groups are working on developing passive UWB tags that work under harsh EM environments. Still another line of effort has been on developing UWB tags embedded on metal surface, a platform where most other RF tags breakdown. A vast majority of UWB tags are currently laboratory prototypes. Our goal in this chapter is to develop the analytical concepts of those UWB tag characteristics that allow UWB tags to have an advantage in RF sensor communication systems.

A key objective in this chapter is to illustrate how UWB signals and systems have evolved to address the challenges of designing RF sensors and transceivers, specifically in addressing the challenges of designing *long-range passive* tags. While there are some important differences between UWB and conventional RF systems, there are also many similarities. Needless to mention, the underlying physics of electromagnetism is of course the same. So as we emphasize the unique features of UWB systems, we must also remind the reader to be familiar with some recently published excellent books and articles in the general area of RF tags [1–5]. For example, some of key circuit theory techniques such as *charge pumps* that have brought RFID systems into the arena of practicality are discussed in [3]. Also the topic of wireless power transfer is covered in great detail in [4, 5]. The list of such references would be too long to be comprehensive, but much of our discussions in this chapter, can be viewed as a summary of journal articles, presentations, and books available in

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the open literature on UWB and RFID systems. We select a few topics here to emphasize those features in RF tags in the context of ultra-wideband RF pulse communication.

It is useful to begin with a model that describes the tag reader/interrogator and its interaction with the tag. We refer to this as the *Remote-Powering Modulated-Backscattering* (RPMB) model. In the previous chapters, we discussed UWB signaling; here we consider how UWB systems help address the technical challenges in the context of the tasks that need to be performed, using the RPMB model. The tasks in the *RPMB model* can be broken down into three steps or stages:

Stage 1: Remote powering of a tag battery or capacitor;
Stage 2: Modulation of the tag antenna using switching logic at the tag;
Stage 3: Reading (or interrogating) the modulated backscattering phenomenon at the tag antenna by a remote reader.

The RPMB model is useful because it allows us to answer some key questions such as:

1. When and why are UWB pulsing more suitable for remote powering (a task performed in Step 1 in the RFMB model)?
2. What are the design advantages or disadvantages of wideband modulation of the tag antenna (a task performed in Step 2 of the RPMB model)?
3. What are the benefits of sensing the modulated backscattered signal at the tag using wideband or ultra-wideband signals (a task performed in Step 3 of the RPMB model)?

Before delving into the technical issues of the RPMB tasks, we need to review some of the relationships of UWB systems and then address the design techniques commonly employed for the engineering implementation of UWB systems. What is the relationship between communication systems and RF tags? What is the relationship between radar and RF tags? Not surprisingly, from these discussions we will see that much of the underlying theory and analysis of RFTAGs are developed using well-known concepts that originates from the fields of RF communications and radar. The discussions also lead us to identify the key challenges of developing passive RFTAGS: (a) remote powering; (b) extending the read range; (c) achieving high data-bandwidth with a low power; and (d) developing efficient antennas. Finally, we conclude this chapter with a summary of regulatory issues for both narrowband and UWB RFID technologies, and point out that ultimately both theoretical and regulatory specifications limit the performance prediction of a new technology.

4.2 UWB Signals and Systems

To complete our discussions in the previous chapter on the advantages of UWB signaling for RFID systems, in this section we the first develop the concepts of UWB signal generation in terms of device technology and implementation.

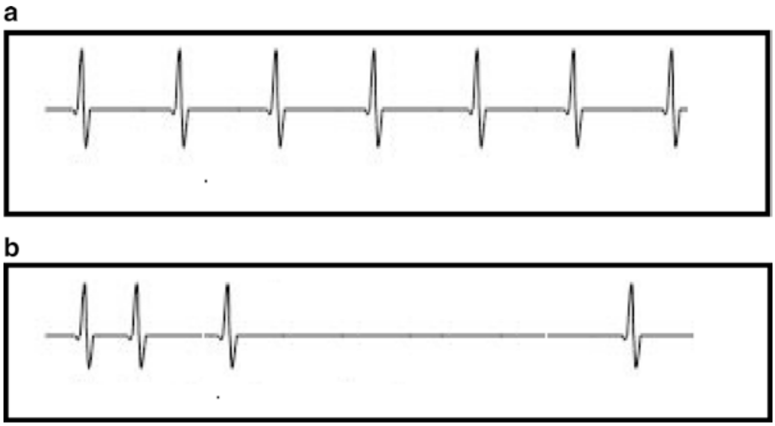


Fig. 4.1 Ultra-wideband RF pulses (**a**) periodic signals (**b**) aperiodic signals

4.2.1 UWB Pulse Operations and Implementations

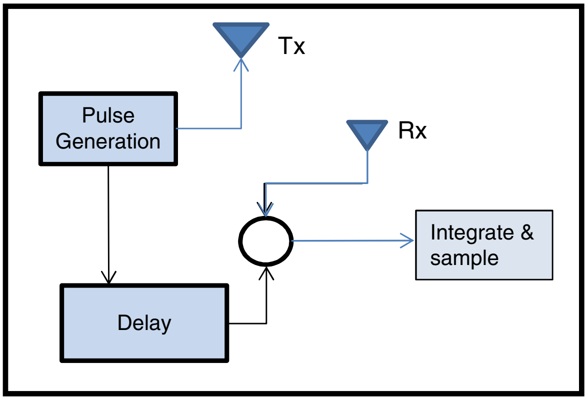
UWB signals can be represented as a sequence of pulses consisting of a periodic (or aperiodic) train of short-time duration microwave RF pulses, each pulse having duration of few 100 ps to less than about 2 ns as shown in Fig. 4.1.

The set of signal processing operations that are performed on these wideband short-duration RF pulses are just a few, and well-defined. For example, as illustrated in the Fig. 4.2, consider a simple ideal match filtering operation that is commonly performed in UWB radars or communication systems.

A circuit, with an accurate time base, triggers the generation of pulses at a certain pulse repetition frequency (PRF), typically a few MHz. Wide beam antennas are often used to directionally emit the UWB EM pulses; with the horn antenna, a directional beamwidth of 120° might be typical. The length of the short UWB pulse determines the pulse bandwidth, a quantity that might vary from a few hundreds of MHz to a few GHz. In terms of signal processing, the transmitter and receiver operate directly on the pulses without intermediate frequency stages that are common in traditional microwave electronics, thus making UWB sensors inexpensive to produce.

Referring again to Fig. 4.2, the main operations performed for match filtering with UWB signals are *delay, multiplication, integration* and *sampling*. We note that the use of an accurate time base is critical in these operations. One usual assumption in these operations is linear phase response (i.e. the signal shape is preserved by the operation). Hence, wideband linear phase amplifiers, multipliers, and delay lines are essential building blocks in UWB transceivers. While the linear operations are conceptually simple, developing wideband delay lines with linear phase response characteristics, for instance, poses an implementation challenge in designing UWB circuits. Mixers are available for narrowband systems, but the implementation of wideband multipliers requires some clever circuit designs. These challenges have been solved in recent years and numerous designs have been developed by many.

Fig. 4.2 The UWB matched-filter



Sampling the UWB pulses in time is yet another challenge: How does one sample a signal with a bandwidth of 1 GHz? Cleary brute force A/D sampling will not lead to a low-cost or low-power solution. *Equivalent time sampling,* it turns out, is a key technique used for the sampling of UWB signals. The equivalent time sampling technique is discussed in Sect. 4.2.3 in detail. Because of the high-frequency wideband nature of the pulses, sampling generally occurs in the baseband, and equivalent time sampling avoids the need for high-power A/D and large memory capacity for signal processing.

In summary, pulse based UWB signal processing is significantly distinct, and in many instances have advantages over conventional narrowband system implementations. Because many wideband RF pulse operations in UWB systems are implemented by cleverly crafted circuits based on the non-linear features of diodes and transistors, expertise in both analog and digital circuit design is a critical element in UWB system design and development. Before discussing the implementation aspects of UWB signal generation at device level, it's important to cover the mathematical representation of UWB signals and their key parameters that allow the engineering implementation of UWB systems.

4.2.2 Mathematical Representation of UWB Signals

In this subsection we develop a mathematical representation of UWB signals for analysis and simulations. As an example, one analytical representation of a UWB pulse is the Gaussian first-derivative shown in Fig. 4.3 and given by the expression:

$$p_1(t) = \frac{t}{d}\exp\left\{-\tfrac{1}{2}\left(\tfrac{t}{d}\right)^2\right\} \tag{4.1}$$

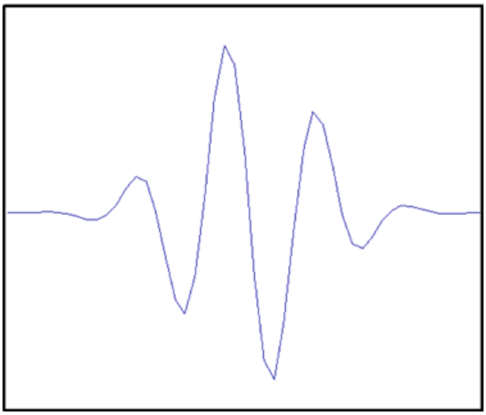


Fig. 4.3 UWB pulse as the Gaussian first derivative. The x-axis represents time and the y-axis represents pulse amplitude. Typically the pulse duration is less than a couple of nanoseconds

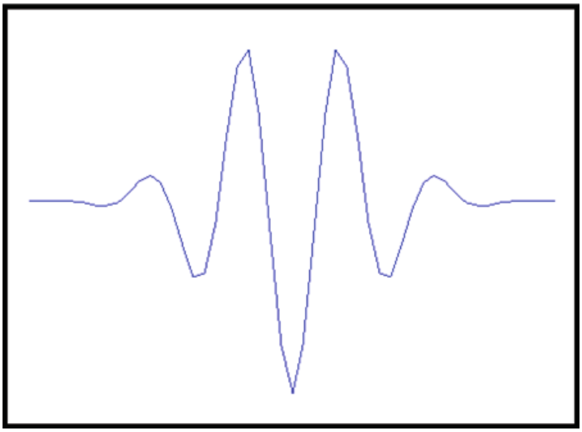


Fig. 4.4 The Gaussian second-derivative representation of an UWB pulse

Where $p_1(t)$ represents amplitude as a function of time, t; and d is a parameter that represents the inverse of the pulse bandwidth. The corresponding Fourier transform of this pulse is given by:

$$P_1(f) = \kappa_1 \, d^2 f \exp\left\{-\frac{(2\pi df)^2}{2}\right\} \tag{4.2}$$

where $\kappa_1 = (2\pi)^{\frac{3}{2}}$.

Another more commonly used representation is the Gaussian-second-derivative which approximates UWB pulses more accurately from EM pulse propagation and antenna response viewpoint. The Gaussian second-derivative representation of an UWB pulse is shown in Fig. 4.4 and given by:

$$p(t) = \frac{1}{d}\exp\left\{-\tfrac{1}{2}\left(\tfrac{t}{d}\right)^2\right\} + \frac{t^2}{d^3}\exp\left\{-\tfrac{1}{2}\left(\tfrac{t}{d}\right)^2\right\} \tag{4.3}$$

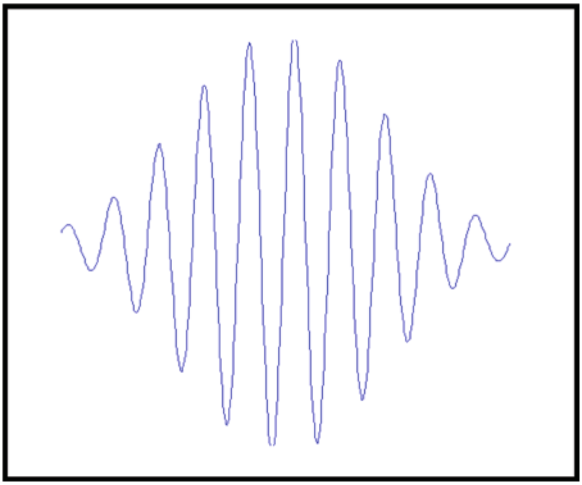


Fig. 4.5 Representation of a UWB signal by the windowed-sinusoidal pulse

The corresponding power spectrum of the above function is given by:

$$P(f) = \kappa\, d^2 f^2 \exp\left\{ -\frac{(2\pi df)^2}{2} \right\} \tag{4.4}$$

where $\kappa = (2\pi)^{\frac{5}{2}}$.

Still another representation is the windowed-sinusoidal pulse of duration T seconds shown in Fig. 4.5, and defined by:

$$s(t) = \cos(2\pi f_c t + \phi) \times \mathrm{w_T}(t) \tag{4.5}$$

where $\mathrm{w_T}(t)$ is a rectangular window of duration T seconds. Now the corresponding power spectrum of the windowed sinusoidal pulse is given by:

$$S(f) = \left[\delta(f + f_c) + \delta(f - f_c)\right] * \mathrm{W_T}(f) \tag{4.6}$$

From these expressions and examples of signals, it becomes clear that although narrow UWB pulses are sometimes referred to as “impulses”, in reality impulse or delta functions are mathematical abstractions and it is more realistic to view microwave UWB systems as systems concerned with short pulses rather than impulses. Most ultra-wideband pulses have pulse duration in the range of 0.1 – 2 ns, a characteristic of short RF pulses in the microwave region of the EM spectrum.

On the other hand, because the Gaussian second derivative (Fig. 4.4) is “more impulsive” than the windowed sinusoidal (Fig. 4.5) representation, the Gaussian second derivative is generally the usual representation in the literature of UWB systems. In UWB systems, a sequence that has a low average power (with a higher peak power) is generally preferred from the public regulatory viewpoint. With respect to UWB tags, it also turns out that a high peak power pulse is more efficient in remote powering of tags, a point that will be discussed in Sect. 5.3.7 of this book.

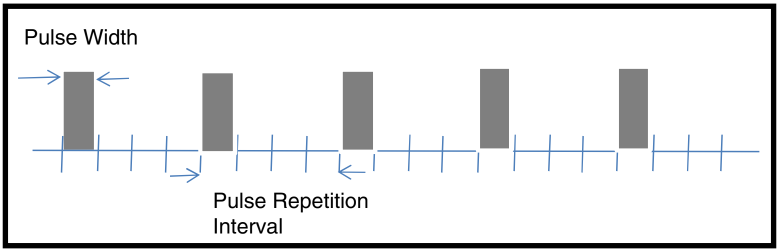


Fig. 4.6 Representation of the pulse width and pulse repetition interval in UWB signals

As we move up the spectrum into higher frequencies, it becomes increasingly difficult to work with signals that have small fractional bandwidths, as phase instability, or phase jitter of local oscillators (LO), can become a limiting factor. Hence, there is a real need to increase the fractional bandwidth for high-frequency low-power (i.e. low average power) systems. Currently although most UWB systems appear in the form of microwave RF devices in the 3 GHz to 10 GHz, one can expect in the near future that UWB systems will be developed for millimeter wave and even terahertz (THz) devices. Operations such as sampling, delay, addition, multiplication and other mathematical operations that are approximated by non-linear diode circuits is bound to play significant roles in developing digital signal processing algorithms in analog hardware. In the following sections we discuss some of the key features of UWB signals that allow engineering implementation of UWB systems including pulse generation, baseband sampling, and the *repetitive* sequence of these pulses that allow baseband signal reconstruction and improvement of SNR by pulse averaging.

4.2.3 Pulse Repetition Frequency of UWB Signals

Because of the short duration of any single pulse, UWB systems generally employ multiple pulses in radar, communication, and tagging applications. In the following subsections, we summarize the features of signaling when pulses are repeated in time.

4.2.3.1 Average and Peak Power

The average transmitted power is the power of the transmitted sequence of pulses averaged over the transmission interval. With a periodic train of pulses, we need to average over the pulse repetition interval (PRI). For example, if a transmitter has a peak power of 10 W, a pulse width (d) of 1 ns, and a pulse repetition frequency (1/T) of 1 MHz, the average power is given by the following equation:

$$Pavg = Ppeak * \left(d / T\right) = 1Wx\left(10^{-9} / 10^{-6}\right) = 1mW$$

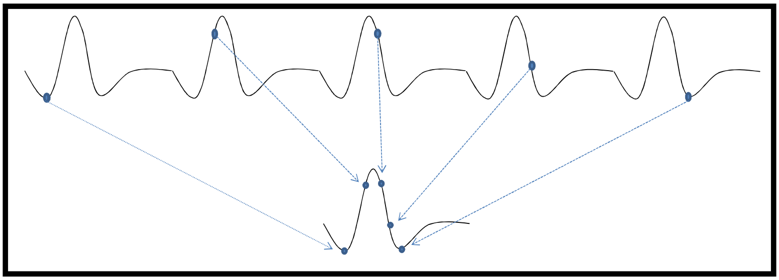


Fig. 4.7 The equivalent time sampling operation

where d/T is the duty cycle and PRF = 1/PRI. For real devices, there is generally a tradeoff between peak amplitude and pulse repetition frequency. This tradeoff has important implications in terms of range and capacity, in the design of long-range passive tags as larger amplitudes in the signal are useful for longer range communication.

4.2.3.2 Equivalent Time Sampling

While the value of a large bandwidth is well-known in radar and communication applications, the implementation of wideband or ultra-wideband reader as a radar system (more discussion on radar as reader is in Sect. 4.3) falls into two distinct categories: impulse radars and swept frequency radars. Most conventional designs of wideband or ultra-wideband radar employ the *swept-frequency* or *chirped signals* to achieve the wideband response. In swept-frequency radar, essentially the radar is scanned at different frequencies and the returns from all frequencies are combined to form a wideband radar return. The process of sweeping over a large number of frequencies can slow down the data acquisition time significantly. Unlike swept-frequency technology, the UWB radars often use the *equivalent time (ET) sampling* or *time expansion* technique. The ET waveform is re-constructed from sequential sampling of the return signal, a sample at each pulse repetition interval and with each successive pulse the sampling point range being incremented slightly. After a large number of pulses, the complete sweep essentially reconstructs the wideband return signal. The operation of ET is illustrated in Fig. 4.7.

It is also instructive to write the ET sampling analytically. Assuming the duration of the UWB is much shorter than the pulse repetition interval (PRI), *T*, the ET operation essentially generates a *discrete sequence*, *p(m)* (separated in true time by Δ, a quantity that represents the delay for each successive sample):

$$p(m) = \sum_n \int_t dt\; p(t - nT)\; \delta(t - m(T - \Delta)) \tag{4.7}$$

In other words, in ET sampling, a delayed copy of the pulse is once again sampled with an incremental delay. The delay gating operation potentially filters out all other

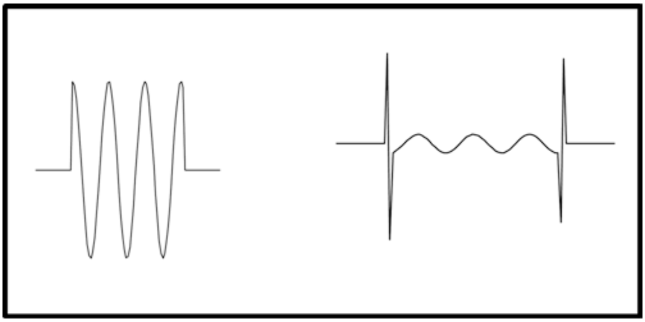


Fig. 4.8 A rectangular box car function (*left*), its and its second derivative (*right*)

incoming energy outside a narrow time window. Such a design reduces the component cost in avoiding the power required with mixers for baseband sampling and also avoids the high cost A-to-D components while reconstructing the wideband returns at high speeds. Hence, the UWB systems can be implemented for high-speed scanning and processing of short pulse signals. One particularly useful signal processing insight into equivalent time sampling was described in a paper by Remley et al. [6], where the analogy of the microwave mixer and the sampling oscilloscope is compared by observing the spectrum of the two operations.

4.2.4 UWB Pulse Generation

Another common problem would be, what is the best way to generate the short UWB pulses? Recall that in signal processing, the differentiation operation enhances the edges of a smooth square pulse. In other words, the "edge effects" due to a differential operation on a signal results in a much shorter pulse (with higher frequencies) features compared to the original pulse. In order to see this phenomenon, consider differentiating a rectangular box-car function shown in Fig. 4.8.

Similar to the differential operation, the UWB circuit as illustrated in Fig. 4.9 below employ a combination of high-pass filtering (or differentiation) operation followed by non-linear diode switching to generate the short-duration UWB pulses.

The functional description of the circuit is outlined as follows [7]:

- Output of a TTL square wave generator drives the transistor circuit into saturation.
- Unlike the slow rise time of TTL, the square-wave of the SRD/avalanche circuit has a faster rise time.
- Differentiation and filtering of negative components occurs with the next set of pulse sharpening operations to generate the train of UWB pulses.

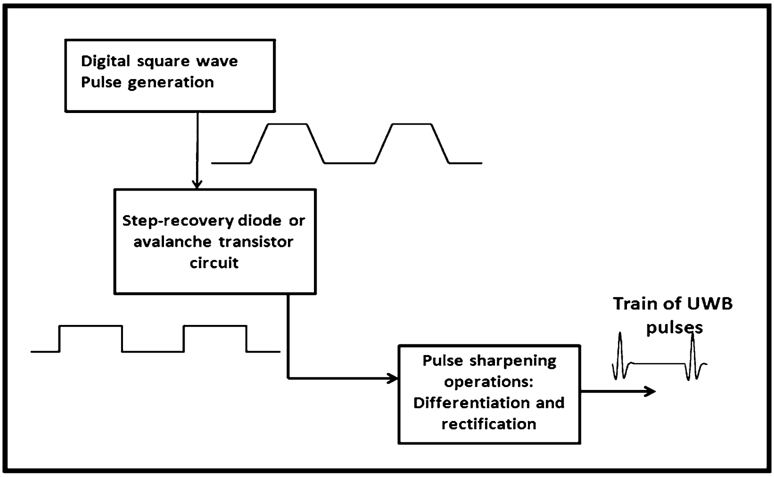


Fig. 4.9 Pulse generation circuit

In general, as illustrated by the above example, UWB pulses are generated by pulse sharpening operations starting from a digital square wave generator. From a signal processing viewpoint, the operations are differentiation followed by switching; and from a circuit device theory viewpoint, one exploits the abrupt non-linear effects of the diode discharging effects.

There are many methods for generating UWB pulses. Avalanche transistors are useful for generating high voltage (20 V) pulses, but these devices are not easy to integrate. Step recovery diodes (SRDs) also generate high voltages of the order of 100 V and they are fast and straightforward to integrate. Hence, we discuss SRDs in more detail.

One of the best and earliest comprehensive discussions on SRDs is the Hewlett Packard Application Note [6]. This article describes in detail how the ability of SRD to store charge and change impedance levels rapidly can be exploited to generate extremely fast rise time pulses and also to shape waveforms. Consider the transition period when a forward biased diode is switched to reverse bias. For a short time just after the switching, the residual charge still allows diode conduction until the residual charges are eliminated. This conductance as a function of time depends on how fast the residual charges are depleted. When conductance stops rapidly the *sudden or impulsive* non-linear change in conductance generates the fast high-frequency switching pulse, or an "impulse" waveform.

While SRD technology is still the workhorse of UWB pulse generation, there are multiple research directions that are being currently pursued for UWB transmitters, from low-power all digital 90 nm CMOS [8] to high-power UWB pulse generation systems as discussed by Agee et al. [9].

4.2.5 Baseband Diode Sampling

Sampling of a short-duration pulse is another important operation in UWB systems. Diodes circuits have been used widely to sample high-frequency wideband signals. For example, a detailed description of the above sampling circuit, in the context of a sampling oscilloscope, is discussed in [10]. From these discussions we see that although most algorithmic level operations are linear in UWB systems, the circuits and devices used in UWB technology often employ and rely on non-linear characteristics of specialized diodes and transistors, such as the step recovery diodes and avalanche transistors. Because these non-linear devices behave as switches, an important residual feature of UWB systems is that they generally consume low power in spite of using signals with very high frequencies and bandwidths.

4.3 Communications, Radars, and Tags

In this section we describe UWB tags from a systems design perspective. An RF tag is a special bi-directional communication system. Let us examine more closely where the modulation and demodulation operations occur in this communications link. This discussion is intended to provide intuition in designing long range passive UWB tags.

4.3.1 RF Tags: Remote Sensing of Modulation

An important difference between an UWB RF tag and other communication systems is that the modulation and demodulation operations of an RF tag system are transposed with respect to the modulation and demodulation of a communication system (see Fig. 4.10).

The implications as to where the modulation and demodulation occur is important. Shannons capacity theorem relates capacity to both bandwidth and received power (or SNR.) The data capacity in a typical communication system is primarily bandwidth-limited, whereas in an RF tag the data capacity is limited by the received signal power, and not primarily bandwidth when UWB pulses are employed. Let us consider some specific examples discussed below.

Recall Shannon's capacity theorem for additive white Gaussian noise,

$$Capacity(C)\,[bits/s] = Bandwidth(W)[Hz] \times Log_2\left(1 + {}^{S}\!/\!_{N}\right)$$

For a bandwidth of 7 GHz and SNR = 0.1, the data capacity, C, is about 667 Mbits/s, a very large data capacity; so we must ask under what conditions? The

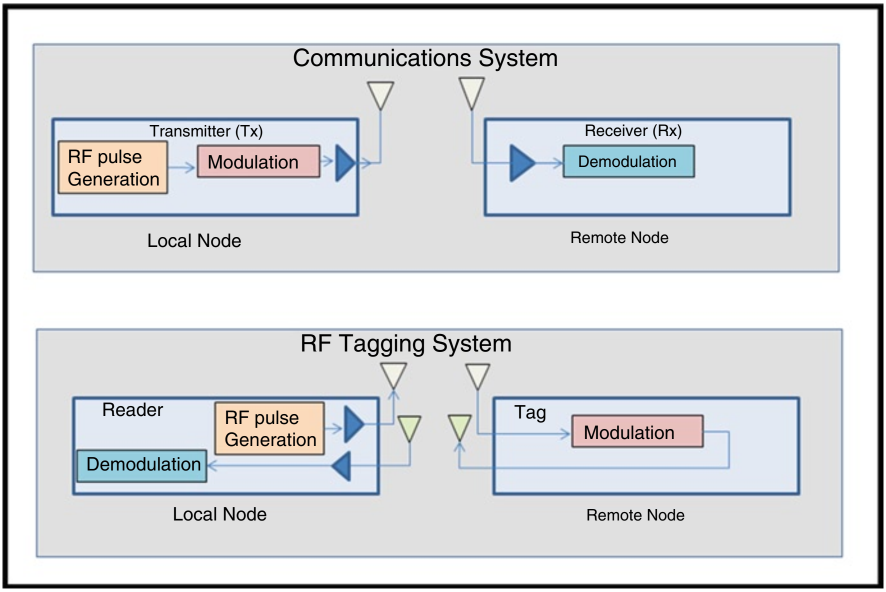


Fig. 4.10 Relationship between a communication system and a tagging system from a modulation viewpoint

example just considered is a low SNR case. In reality, two special cases are of interest are considered below:

Case I: High SNR Communications (SNR >> 1):

$$C \approx BW$$

Hence, when the SNR is very large, capacity is limited by signal bandwidth. Therefore for short range UWB RF tags, when the SNR is very high, UWB tags might have significant advantage in terms of data capacity. So as we tags are integrated withsensors, and applications require not only tag identification but also data exfiltration from the tag to the interrogator, UWB tags can be theoretically very powerful sensor communication devices.

Case II: Low SNR (SNR << 1)

One can show:

$$C \approx BW \times SNR$$

Therefore, for long-range high-bandwidth UWB systems (and SNR << 1), such as long-range UWB RF tags systems, we have:

$$C \approx \frac{P_R}{kT} \; / \ln 2$$

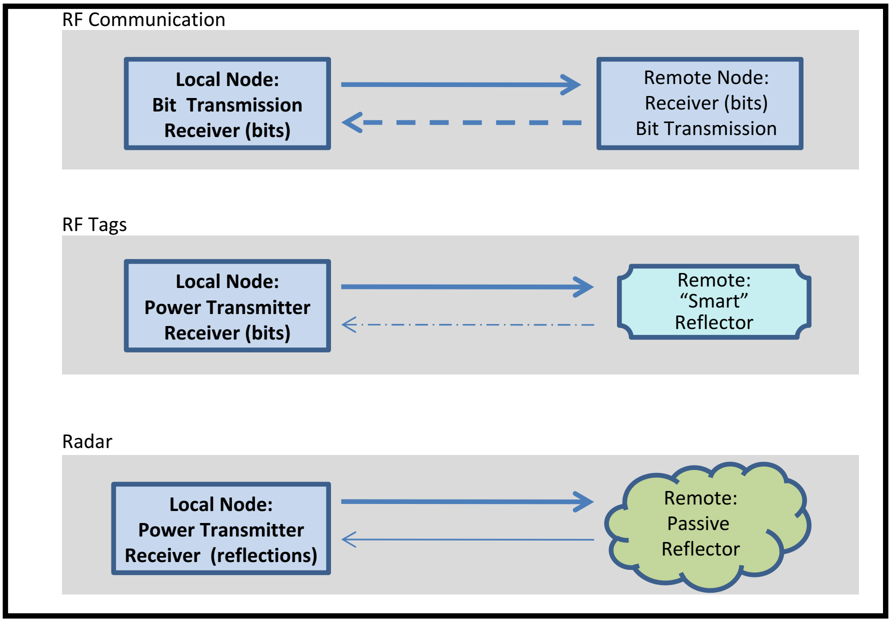


Fig. 4.11 An RF tag system can be viewed as a hybrid between a duplex communication systems and radar system. The remote node in a RF tag is a passive, but a smart reflector

kT is equivalent to 4.11×10^{-21} J (or −174 dBm). In decibel scale, the power at the receiver, P_R, is given by $P_R\,(dBm) \approx 10 * \log_{10}(C) + 10 * \log_{10}(kT) + \log_{10}(\ln(2))$. From the equations above we see that the capacity or range of such a system can be increased by a increasing the PRF (high PRF leading to higher average power). Alternatively using large-peak-amplitude and low PRF UWB pulses (i.e., large peak power UWB and low average power), one can design longer range low-capacity UWB tagging systems. In UWB RF tags since modulation occurs at the remote node, efficient wireless power transmission is therefore a key function. Given the limitations of the physics of RF devices, such as diodes, and the geometrical losses $(\frac{1}{R^2})$, large peak power transmitters are most efficient in terms of remote powering.

In some design, options powering of the tag can be decoupled from interrogation of the tag with a longer range "radar reader" that deciphers the RCS modulation of the tag antenna. Hence, the design innovations for long range UWB tagging system can be expected by focusing on the design of compact readers.

Finally, when the range between the transmitter and receiver nodes is known, a large peak-power system can also be employed for high-bandwidth communication using multilevel (multiple amplitudes) modulation techniques. In other words, it is not necessary to have a high PRF for high data rate (capacity in bits per second) UWB communication.

An instructive way to view RF Tags would be to view the systems as a hybrid system – consisting of *radar* and a *duplex communication system*, as depicted in Fig. 4.11.

4.3.2 RF Tags from a UWB Perspective

In radar, the “reflector” is an assumed or an unknown quantity (the exact RCS of the reflector is just an estimate) and the design focuses on the transmitter and receiver on the “local” platform. In communication systems, the design focuses on the receiver and the transmitter of “bits” (or information), the remote platform and the local platform. What makes passive RF tags a unique technology is that their design introduces the following challenges:

1. The design of a remote smart reflector
2. The design of a local power transmitter; and
3. The design of a local demodulator or “bit” receiver.

We discuss later in this chapter that the design of a smart reflector requires “remote powering” (or “power scavenging”) and modulating the RCS of the reflector. Hence, to address the question why UWB is relevant in RF tags, we must first review how UWB is advantageous for both communication and radar systems, and also how UWB allows effective long-range remote powering systems.

Note that the long-range remote powering design issues (i.e. passive UWB tag design challenges) are quite different from the short-range near-field RFID tags. Near-field RFIDs in the 13.56 MHz band have been in existence for many years and require close proximity between the reader and the tag, generally a distance of less than 1 m, to establish an EM coupling between the coils of the tag and the reader antennas. The low frequencies or long wavelengths allow the signal to go through obstacles. The skin depth is also higher at the lower frequencies. Hence, the near-field RFIDs have many useful features for very short-range applications. For longer-range applications, however, near-field RFIDs are generally not applicable.

For longer-range applications, far-field (refer to 2.2.5) properties of propagating EM waves need to be exploited. In far-field, the EM waves can be well approximated as planewaves; hence use of antenna arrays can also help in terms of wave focusing and improving antenna gain for improved range or SNR. The far-field is commonly defined as

$$d > \max\left(\lambda, \frac{D^2}{\lambda}\right) \tag{4.8}$$

where D is the maximum dimension of the reader antenna, d is the communications distance and Lambda is the wavelength. From the above constraint, we see that for the antenna to have a reasonable gain and a small size, far-field RFID is best designed in the UHF or microwave frequencies. At these higher frequencies material dielectrics, such as conductivity, can have significant effect on the antenna’s complex impedance and therefore on the performance of the tags. The use of wideband signals for frequency diversity, or phase insensitivity, is an important technical motivation for the development of UWB tags.

It is instructive to examine the rectifying antenna model for wireless power transfer with respect to UWB short pulses. For a detailed discussion on the topic of wireless power transfer, the reader is referred to the book, Design and Optimization

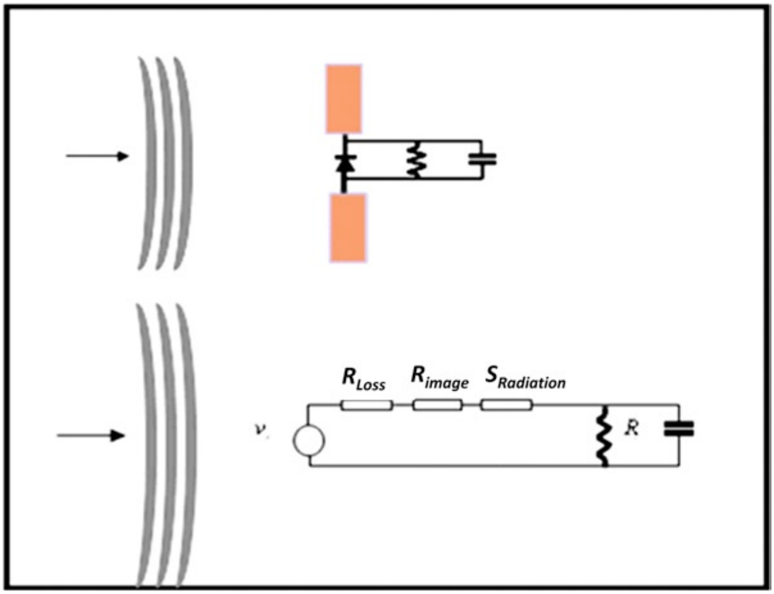


Fig. 4.12 A rectifying antenna (rectenna) model (*Top*) and lumped element model of dipole antenna (*Bottom*)

of passive UHF RFID Systems [4]. Here we address the issues from an antenna design point of view. Figure 4.12 shows a rectifying antenna model with EM field impinging on it.

It can be shown that the power transferred to the capacitor is given by

$$v_c = 2\pi \sqrt{2 S_{Radiation}\, P_{AVG}}\, \frac{R_i}{R_i + R_s} \tag{4.9}$$

which can be re-written as

$$v_c = 2\pi \frac{l}{\lambda} \sqrt{40\, P_{AVG}}\, \frac{R_i}{R_i + R_s} \tag{4.10}$$

where $R_s = R_{Loss} + S_{Radiation}$, assuming R_{imag} has negligible effects. Now if we assume further that loss resistance (heat) can be ignored, we can use the expression for the radiation resistance of a small tag (less than a quarter wavelength) dipole antenna of length *l* as

$$S_{Radiation} = 20\pi^2 \left(\frac{l}{\lambda} \right)^2 \tag{4.11}$$

The antenna receives the EM field and induces a voltage difference at the diode ports. The relations described above are useful in designing RF tags, or remote

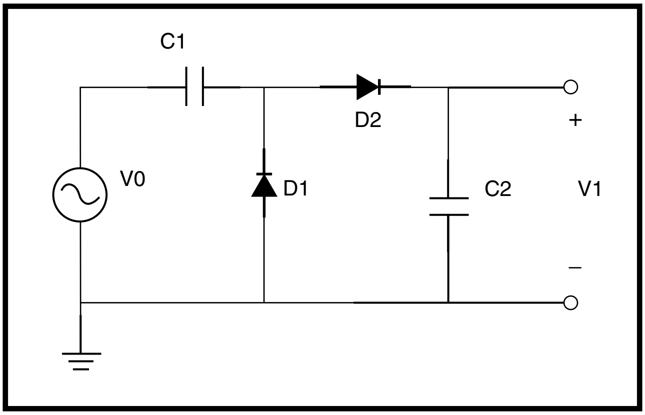


Fig. 4.13 A single stage charge pump

power transfer in particular, because they relate the voltage at the storing capacitor with the radiation resistance of an antenna. The radiation resistance of the antenna represents the strength of the radiated electromagnetic field received by a receiving antenna (or transmitted by the transmitting antenna). This value is directly proportional to the*power*of the field but is also conditioned by the power transfer relationship and the antenna dimensions with respect to the wavelength. The mathematical relationships described above are approximations under simplified assumptions; they are discussed here to indicate how high-frequency wideband signaling allows more variability for the design of optimally small antennas for passive RF tags. For a detailed theoretical discussion on backscattering the reader is referred to the paper by Nikitin and Rao [11]. A practical description of RFID measurements is described in [12].

4.3.3 Use of Charge Pumps for Long-Range Remote Powering of Tags

The received RF signal at the tag, at any reasonable distance, is not powerful enough to drive the logic circuits. In order to improve the power level, a voltage amplifier circuit is employed. This voltage multiplier (or "voltage doubler") is extremely useful circuit for RFID systems as it allows remote powering of the tag IC from the weak signal received at the antenna. Figure 4.13 shows an example of a single stage charge pump.

As shown in Fig. 4.13, when the received pulse is positive, the capacitor C1 gets charged as the diode D1 is forward biased. When the received pulse amplitude goes negative, capacitor C2 is charged due to forward bias at D2. As the circuit reaches its steady state, the voltage amplitude at C1 is "doubled" (increased), or the charge stored at C1 is pumped upwards. What is most interesting is that this circuit can be daisy chained for higher and higher voltages at the output as shown in Fig. 4.14.

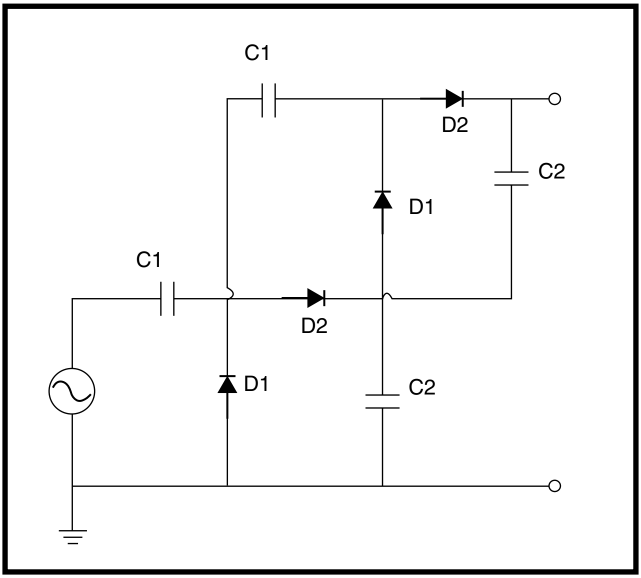


Fig. 4.14 A two-stage charge pump

Referring to Fig. 4.13, the received pulse is rectified by D2 and C2 is charged when the pulse is positive. When the received voltage is negative, D1 is forward biased and C1 gets charged. In the next positive pulse cycle, charges from C1 gets transferred to C2, thereby increasing the output voltage, V2. The key value of this circuit is that by stacking or connecting another stage in series we are able to again increase the voltage. The output voltage is then amplified by a number that is proportional to the number of stages used. For a more detailed discussion on this topic, the reader is referred to references [3] and [4].

It is important to remember that there is a loss due to the diode drop. The diode drop is much more significant for sinusoidal or narrowband input compared to high amplitude impulse waveforms (refer to 3.2.7). Since UWB pulses have high positive (and negative) peak amplitudes, the charge pump circuit is quite efficient and remote powering at long ranges with UWB signaling makes good sense.

4.3.4 Tag Reader using the UWB Radar

In the previous section we discussed how UWB transmitters can be used as a remote powering transmitter. In this section we discuss that the tag reader can be implanted using as a UWB radar. To begin this discussion, let us first review the radar equation:

$$P_{Reader-Rx} = \frac{P_{Tag-Tx} G_{\text{Reader}} A_L \sigma}{(4\pi)^2 R^4} \tag{4.12}$$

where $P_{\text{Reader - Rx}}$ represents the power received at the reader as back scattered from the tag, $P_{\text{Tag - Tx}}$ represents the power transmitted by the transmitting reader, G_{Reader} represents the gain of the transmitting antenna at the reader, A_L represents the effective aperture of the receiving antenna, and σ is the scattering coefficient or the radar cross section of the tag. In order to see the utility of UWB technology for tags, we can re-write the previous equation in terms of the range:

$$R_{Max} = \left(\frac{P_{Tag-Tx}\, G_{\text{Reader}} A_L\, \sigma}{(4\pi)^2\, P_{\text{Reader - Rx,min}}} \right)^{1/4} \tag{4.13}$$

$$R_{Max} = \left(\frac{P_{Tag-Tx}\, G_{\text{Reader}} G_{tag} \lambda^2 \sigma}{(4\pi)^3\, P_{\text{Reader - Rx,min}}} \right)^{1/4} \tag{4.14}$$

Note that doubling the power at the transmitter increases the range by only about 20%. To double the range, the *Tx* power has to be increased by a factor of 16, or a 12 dB additional power.

From the equation above we see that the range is maximized by maximizing the peak power, $P_{\text{Tag - Tx}}$; this calls for a high peak power UWB transmitter. The read range can also be increased by designing a highly sensitive reader by minimizing the $P_{\text{Reader - Rx}}$. This can be achieved by multi-pulse averaging or using a UWB "phased-array" reader.

4.4 FCC Regulations for RFID Systems

RF wireless communications, radar, and RFID systems, like other telecommunications equipment, must meet technical requirements established by national and international regulatory entities. In the United States, FCC regulations for unlicensed devices are described in Part 2, Part 15, and Part 18 of the FCC Code of Federal Regulation (CFR) Title 47, as illustrated in Fig. 4.15.

Active and semi-active (refer to Sect. 1.5.2) RFID tags are actual transmitters and similar to their readers they have to be regulated by FCC rules. These systems are considered as radio frequency devices and based on their frequency of operations; they should follow specific transmission limits. On the contrary, passive and semi-passive RF tags do not actively transmit signals and FCC qualifies them as "unintentional" radiators and do not need to be certified individually. It's important to emphasize that battery assisted (semi-passive) tags do not actively generate RF energy and the on-board battery is only to provide power to the tag circuitry (refer to Sect. 1.5.4). However, passive and semi-passive tag readers are considered as "intentional" radiators and need to be FCC certified and regulated. The regulatory rules and conditions are different for narrowband and ultra-wideband RFID systems and need to be considered while designing them. In the following sub-sections we summarize the FCC requirements for narrowband and ultra-wideband RFID systems.

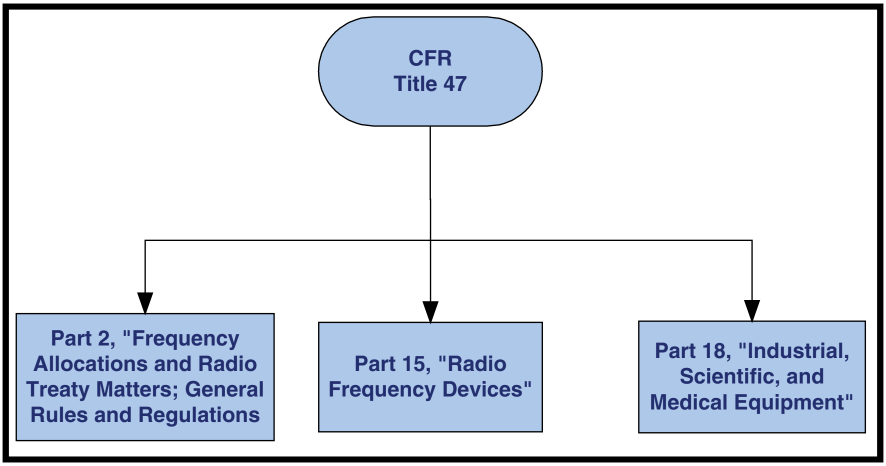


Fig. 4.15 Summary of FCC code of federal regulations, title 47

Table 4.1 FCC allocated frequencies for passive RFID tags in ISM band

Popular frequencies for RFID systems in ISM Band			
13.56 MHz	902–928 MHz	2.4–2.483 GHz	5.725–5.850 GHz

4.4.1 FCC Rules for Narrowband RFID Systems

In order to avoid interference with other radio systems, FCC regulations requires that narrowband passive and semi-passive RFID readers operate in unlicensed ISM bands[1] (shown in Table 4.1) under conditions defined by FCC part 15, section 15.247.

RFID tags in high frequency (13.56 MHz) have short read range and the tags in microwave frequencies (2.4 GHz or 5.7 GHz) have lower penetration properties and they are prone to interference and multipath. Therefore, the optimal ISM frequency region for narrowband passive and semi-passive tags is 902 –928 MHz. FCC regulations in this frequency region state that the maximum output power from a UHF reader to be 1 W, with a maximum allowable antenna gain of 6 dB that translates to 4 W EIRP.[2] In order to take advantage of maximum output power of 4 W EIRP, FCC mandates that RFID readers in 902–928 MHz frequency region utilize frequency hopping spread spectrum technique and hop between 50 channels (500 KHz each) without staying on any channel for longer than 400 ms when averaged over a 10 s. window.

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[1] ISM is defined as Industrial, Scientific, Medical band. Radio devices are allowed to operate in ISM band without any license, provided that they are certified by the regulatory organizations for following the rules and conditions defined for this band.

[2] EIRP is defined as the effective isotropic radiated power which is equal to transmitted signal power from an ideal omni-directional (isotropic) antenna.

Table 4.2 HF passive RFID regulations allow the same frequency with different power level for different parts of the world [13]

Region	Operating frequency (MHz)	Maximum power (W)
North America	13.56	3
Canada	13.56	3
Europe	13.56	4

Regulatory requirements such as operating frequency and maximum allowable output power for UHF RFID systems operating in ISM band vary from country to country (refer to Sect. 2.2.6). A detailed representation of worldwide regulatory requirements for RFID systems at ISM band is available at [13]. Unlike, UHF passive RFIDs, the 13.56 MHz operating frequency for passive high frequency (HF) systems is acceptable worldwide. The only difference between HF passive RFID readers in different regions is the maximum allowable output power as shown in the Table 4.2.

4.4.2 FCC Rules for Ultra-Wideband RFID Systems

As we described in Sect. 4.4.1, the passive and semi-passive UWB tags do not need to be regulated and only the readers need to follow the FCC regulations. Hence, in the case of UWB RFIDs, the active and semi-active systems (both tags and readers) as well as passive and semi-passive systems (only the reader) have to be certified based on the FCC regulations that were mandated on February, 14th of 2002.

FCC allows the unlicensed UWB transmissions for commercial purposes in 3.1 GHz to 10.6 GHz under part 15 classification that places UWB signals in the category of "unintentional" radiators [13–15]. Since UWB signals cover a large portion of RF spectrum accessing restricted bands and incumbent licensees, FCC requires a conservative power mask on such transmissions to avoid harmful interference to any legacy services. This power mask allows UWB signals to transmit with an average EIRP level of −41 dBm/MHz (75 nW/MHz).[3] FCC's power limits for

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[3] FCC Specification per MHz bandwidth is –41.3 dBm = 500 microvolts at a distance of 3 m. The radiated power density (P_{EIRP}) can be calculated from the following equations:

$$\frac{1}{2}\left|E\times H^*\right| = \frac{|E|^2}{2\eta} = \frac{P_{Tx}G_{Tx}}{4\pi R^2} = \frac{p_{EIRP}}{4\pi R^2}$$

$$P_{EIRP} = \frac{|E|^2}{377}\times 4\pi R^2$$

Where E represents electric field, H^* is the conjugate magnetic field, n is the free space impedance, P_{TX} is the transmit power, G_{TX} is the transmit antenna gain, and R is the distance from transmitter.

Table 4.3 Emission limits for UWB RFID transmissions in each operational band [13]

Frequency of operation (GHz)	Indoor EIRP (dBm)	Outdoor EIRP (dBm)
0.96 – 1.61	–75.3	–75.3
1.61 – 1.99	–53.3	–63.3
1.99– 3.1	–51.3	–61.3
3.1 – 10.6	–41.3	–41.3
10.6 – 22.0	–51.3	–61.3
22.0 – 29.0	–51.3	–61.3

UWB transmissions is even more restricted near GPS band (0.96–1.61 GHz) with maximum EIRP power limit of −75 dBm/MHz (12 nW/MHz). Although FCC's power mask for UWB transmissions is different for various applications such as communications, radar, and imaging, the rules that apply to UWB RFID systems are the ones that are defined for communications systems. Table 4.3 summarizes the FCC mask for average PSD of UWB RFID readers in various parts of the frequency spectrum for indoor and outdoor applications.

As shown in Table 4.3, UWB emissions for indoor and outdoor communications devices have different out-of-band emission limits. In addition to the average PSD level requirement for UWB transmissions, FCC mandates a limit of 0 dBm (1 mW) peak power limit on transmitted UWB pulses center frequency in a 50 MHz resolution bandwidth. Furthermore, FCC requires that the peak emission level over the entire 7500 MHz of UWB spectrum should not be more than 60 dB of average power ($P_{Peak} < P_{Ave} + 60$ dB).

Under the original rules defined by FCC in 2002, UWB transmitters had to be tested with "full" transmission power even if the device had any internal power saving capability such as gating or low duty cycle. In March 2005, a waiver from FCC allowed UWB transmissions to be tested only at transmission time [16]. This waiver allows UWB RFID systems to have better performance by transmitting higher peak power provided that the signals are gated and the average power does not exceed the FCC emission mask at various frequencies. Specifically, passive UWB RFID readers can benefit from the high peak power to power up a tag from longer distances, and remain quiet for a period after powering to meet the average power limitation.

4.5 Summary

In this chapter, we developed the relationships between communication systems, radar and RF tags in order to understand the various advantages of UWB RF tags with respect to designing low-power low cost RF tags. These relationships can be used to develop high performance UWB tags for special applications. In particular, we see that for mid range (<10 m) passive RF tags, the UWB RF tags might be particularly attractive for high data rate systems because of the high-bandwidth available. High-data rate tagging system can be useful when tags are integrated with sensors for remote monitoring or developing encryption and authentication capabilities onto to RF tags.

We also covered the implementation aspects of UWB RF tags by discussing concepts such as UWB pulse generation, baseband diode sampling, remote powering, and use of UWB radar as the tag reader. FCC regulations for UWB RF tags were discussed in the final sections of this chapter which showed from a range perspective, FCC regulations will be the limiting factor for a building very long long-range passive UWB RF tag. However, because of the available bandwidth, from a viewpoint of tag positioning, UWB RF tags can be extremely attractive.

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Chapter 5

Antenna Design for Ultra-wideband Passive RFID Systems

5.1 Introduction

Antennas are one of the key components of all RF wireless communication and radar systems, including RFIDs, as they are responsible for the transmission and reception of free-space or through-barrier weak electromagnetic (EM) signals. The optimal design of antennas for a wideband EM wavefield continues to be an area of important research, one that is rapidly growing in many different fronts. For example, recent interest in the use of *meta-materials,* materials with unusual dielectric properties, for designing the radiation pattern of antennas to reduce the size and cost of wireless components could lead to important antenna breakthroughs for RFID tags. Another area of antenna research involves the use of *nano-structured materials,* for improved characteristics such as mechanical robustness, radiation-efficiency, directivity, and reduced antenna size. These new and exciting research areas are however beyond the scope of this chapter. Our goal in this chapter is to discuss the main technical issues of wideband antennas for RFID systems and to identify several design options that might enable the interested readers to pursue research in RFID antenna design, including exploring other emerging concepts and technologies.

It is important to emphasize at the outset that in this chapter (and also for this book in general) that we are concerned with long read-range RFID systems where the reader and the tag communicate using propagating EM wavefields. The design issues of far field UWB RFID systems, topics discussed in this chapter, is quite different from the antenna design issues of inductively coupled RFID systems where the tag and the reader are coupled by inductive fields, a near field phenomena.

In this chapter we survey a number of different antenna design options proposed in the literature for wideband reader and tag antennas and discuss methods that one might wish to adopt to improve RFID design specifications such as read range and reliability. Another objective of this discussion is to refer the reader to a few of the important publications and books in the context of this subject. This chapter covers a wide range of options for UWB antenna designs for both readers and tags in a UWB

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RFID system. Some of the antenna design techniques discussed in this chapter applies to readers more than tags, and vice versa. Although proper antenna design can improve the performance efficiency of both active and passive RFID systems, we mostly emphasize on the challenge of UWB antennas for long-range passive RFID systems.

5.2 Antenna Requirements for Passive UWB RFID Systems

As mentioned in the previous section, the antenna design issues for a long range UWB passive RFID system falls in the area of far field antenna design. What are the specific reasons that antennas are critical in the design of far field RFID systems? With respect to read range of the RFID system, for a number of RFID applications, one needs to meet a set of conflicting requirements, a situation that is not uncommon in many engineering design problems. In these applications the requirements for the RF tags can be summarized as follows:

- Tags need to be small, often smaller than the size of a credit card. This poses a challenge for the tag antenna because a 1 GHz EM wave has a wavelength of about a foot. The practical tag antenna dimension requirements are often much smaller than a wavelength, hence the antenna gain and directivity becomes a design challenge for low power long range applications.
- The tags must have a very long lifetime, preferably many years. This requirement translates to the fact that the tag should not rely on batteries, and ought to be remotely powered by the reader. The design of small yet efficient antennas for the effective back scattering, with enough power to allow the reader to communicate with tags rapidly (i.e. without pulse integration delay), is a challenge.
- In many applications, reader-to-tag read-range needs to be many meters, much longer than the ranges of the state-of-the-art passive tags. In fact, for some applications, desired distance might be many hundreds of meters. Given that a design must in addition meet regulatory emission limits, the challenge is to develop tags and tag readers with high antenna gain and sufficient reader sensitivity.

Hence, the reader antenna design engineering must use efficient antennas with high directivity and receiver sensitivity to interrogate a distant passive tag, emitting only a weak back-scattered signal. The design of the antenna needs to consider both the antenna geometry and the waveform characteristics.

In terms of the waveform design, the use of ultra-wideband microwave pulses can be effective in the following areas:

- Exploiting frequency diversity for both link reliability and obstacle penetration
- Improving the processing gain from the large pulse bandwidth
- Taking advantage of time diversity using coding of the short-time pulses.

However, it is the antenna that must allow the wideband interface between the electronics and the radiated short-pulse EM field.

Thus a well-designed UWB RFID antenna needs to employ discrete antenna elements with favorable radiation characteristics and also use an array of those antennas for "wideband phased array" processing. The use of these design techniques is practical especially with respect to tag readers, a component that has less restriction than the tag in terms of size and processing resources. In summary, the use of array signal processing and antenna array methods are critical in designing the next generation wideband RFID systems in meeting the challenging requirements outlined above.

In order to discuss the wideband antenna design constraints at an introductory level, we first present a summary of some important and yet basic observations of EM radiation and antenna arrays with some intuitive examples in Sect. 5.3; this allows us to introduce the language of the technical subject matter. For a more rigorous and thorough treatment of antenna and array signal processing theory, readers are encouraged to refer to a number of excellent books and articles such as [1, 2]. In Sect. 5.4, we provide a survey of UWB antennas and present some specific candidate antenna designs for ultra-wideband RFID tags. We briefly cover the area of flexible textile UWB antennas for wearable RFIDs in Sect. 5.5, and finally we end the chapter with a detailed discussion on impedance matching for RFID tags and an overview of the concept of on-chip antennas as a futuristic step for UWB RFID tags.

5.3 EM Field Radiation and Antennas for UWB RFID Readers

In this section, we briefly review some important observations to point out the constraints of wideband antenna design for RFID applications. These observations might also be useful in building intuition about the antenna design problem for UWB RFID systems. The interested reader is encouraged to not only acquire a deeper understanding of antennas by delving into modern and very well-written texts in EM antenna design, such as the texts by Balanis [1] and Strutzman and Thiele [2], but also explore many readable web based discussions on antennas such as excerpts in [3] and its references. For example, the article by Ron Schmitt [4] is a comprehensive introduction into the more rigorous texts on antenna design.

5.3.1 *Remote Powering of Passive Tags in the Far-Field with Propagating EM Waves*

Consider the simplified Fig. 5.1, depicting the near and far field regions near an antenna.

As discussed earlier in Chap. 2, far-field is the region where the receiver distance, r, from the transmitter satisfies the following conditions [2]:

$$r > \frac{2D^2}{\lambda}, r > 5D, and\ r > 1.6\,\lambda \tag{5.1}$$

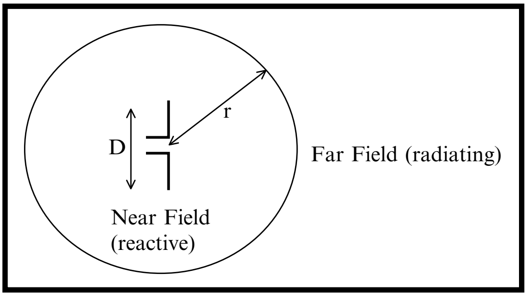

Fig. 5.1 Representation of near and far field regions near an antenna

where λ is the wavelength, and D is the maximum linear dimension of the antenna. Because of the short-wavelength of UWB signals, UWB RFIDs are really far field systems. We note that many narrowband RFID systems are near-field systems, and the tags are inductively coupled with the reader. On the other hand, as briefly discussed in Chap. 3, for far-field UWB RFID systems, reader and tags interact directly with propagating electromagnetic waves.

An obvious observation to keep in mind is that for an omni-directional antenna, like a Hertzian dipole, the power at the receiver (assuming antenna gain of 1) is given by

$$P_{TAG} = \frac{P_{READER}\,\lambda^2}{4\pi R^2_{reader-to-tag}} \tag{5.2}$$

where λ represents the wavelength, $R_{reader-to-tag}$ is the distance from the tag to the reader, and (P_{TAG}, P_{READER}) represents the power received at the tag, and the power transmitted by the reader, respectively. Note from (5.2), for a 1 W transmitter at the reader, with the tag at a 5 m range, and waveform pulse at frequency of 2.4 GHz, the power received at the tag would be only about 50 μ-Watts in free space, and possibly much worse in a multipath environment.

With current device technology this power level is rather marginal. Hence, for long-range applications, directional antenna arrays focusing the energy from readers in certain directions (i.e. antenna arrays with high-directivity) might be the most effective solution.

5.3.2 Antenna Design and Reciprocity Theorems

In the signal processing literature, the analysis of antenna design is usually constructed from the *receiving antenna* viewpoint. On the other hand, in EM literature, often the discussion occurs from the *transmitting antenna* frame of reference. However, the receiver-transmitter “reciprocity” makes this disconnect somewhat irrelevant because from the reciprocity theorem the antenna response are the same for both the transmitter and the receiver.

In the context of antenna design, the array pattern or beam pattern of an antenna is the same for transmitting and receiving arrays. Since an RFID reader is both a transmitter and a receiver, the ability to focus a beam towards the tag during trans-

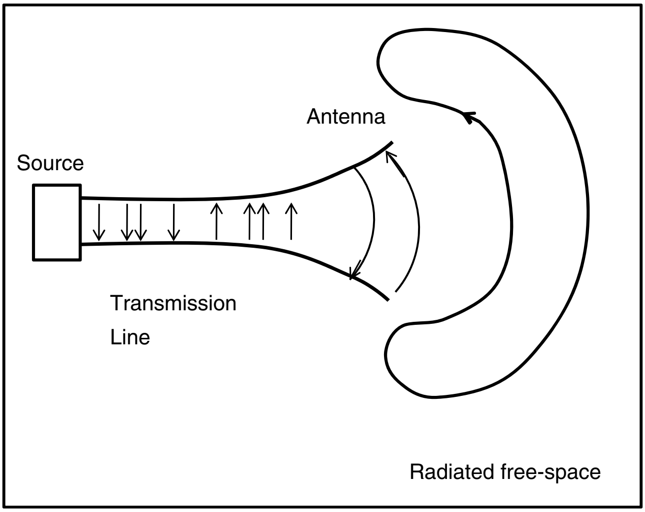

Fig. 5.2 Example of wave radiation due to effects of electron acceleration

mission, and also towards the same tag during reception has implications in terms of being able to develop cost-effective phased array receivers or readers.

5.3.3 EM Radiation Occurs from Acceleration of Electrons

Figure 5.2 illustrates that radiation of EM waves takes place due to charge particles or electrons entering free space at the edge of the transmission line, the antenna, and thus closing the loop of the EM waves and initiating the phenomena of wave propagation in free space [1].

Maxwell's equations below can be used to explain wave radiation phenomenon due to acceleration of electrons at the edge of the transmission lines.

$$\nabla \,.\, \mathbf{E} = \rho/\varepsilon_0 \tag{5.3}$$

$$\nabla .\, \mathbf{B} = 0 \tag{5.4}$$

$$\nabla \times \mathbf{E} = -\mathrm{d}\mathbf{B}/\mathrm{dt} \tag{5.5}$$

$$\nabla \times \mathbf{B} = \mu_0 J + \mu_0 \varepsilon_0 \mathbf{dE/d}t \tag{5.6}$$

Here **E** and **B** represent the electric and magnetic fields respectively, ρ represents the density of electrical charges, ε_0 and μ_0 represent the non-zero dielectric constant (permeability) and the non-zero magnetic constant (permittivity) of the propagation medium, and J and ρ represent the current and charge densities. Maxwell's equations show that acceleration in electrons creates a continuously radiating electric field where the change in electric field generates continuous magnetic field resulting in propagation of electromagnetic waveforms.

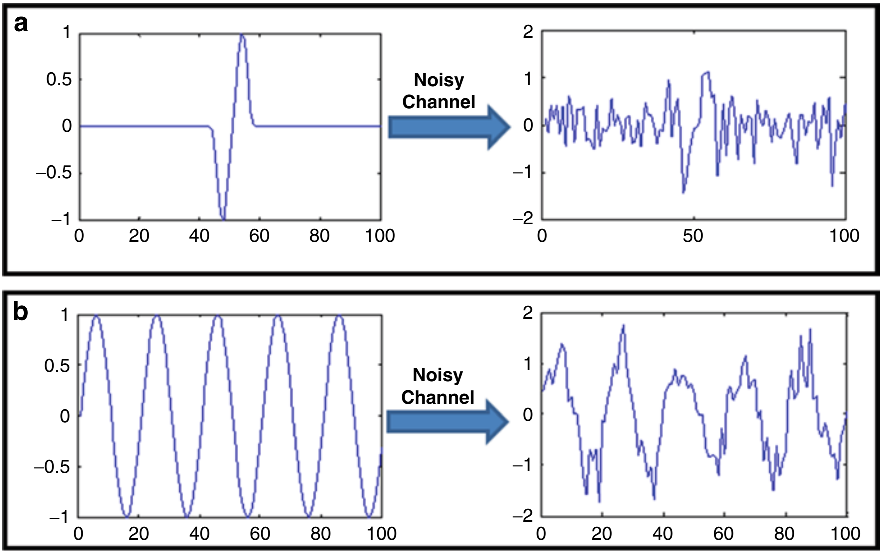

Fig. 5.3 Comparison of (**a**) UWB pulse with (**b**) CW narrowband signal in a noisy channel

Electromagnetic links also tend to deteriorate in the wireless channel due to background noise and interfering signals in the channel. For example, the shape of UWB pulses can severely get distorted due to channel noise as illustrated in Fig. 5.3.

The CW signal has preserved its periodicity and shape in noisy channel so it can be recovered or easily detected by any receiver which can estimate the frequency of the waveform; whereas the UWB pulse is indistinguishable due to noise, and can be detected only by a receiver which already knows the shape of the pulse. The above example shows that narrowband CW signals are less sensitive channel noise than low-amplitude UWB pulses. As the EM UWB pulse radiates, the preservation of the pulse shape is important in ultra-wideband applications, especially for match-filtering processing at the reader's receiver. Hence, the design of UWB antennas is critical for achieving linear phase response over a wideband of frequencies, and thereby preserving the waveform shape. This EM phenomenon is further discussed in [5] in more detail.

5.3.4 Non-Resonant UWB Antennas

Most antennas are resonant systems and therefore have a narrowband frequency response. The challenge in UWB antenna design is to develop antennas which have a non-resonant wideband frequency response. The frequency response of an antenna can be crafted by shaping the three-dimensional shape of an antenna. For example, while dipole antennas are generally resonant and have narrow bandwidth, their bandwidth can be improved by increasing the widths of the dipole geometry [2]. The horn antenna is a classic example of this approach towards wideband antenna design.

The microstrip patch antenna is also an interesting antenna as it allows some flexibility for wideband design. The microstrip antennas are printed on dielectric circuit boards with a dielectric material sandwiched between a conductive patch and ground plane. The fractional bandwidth of microstrip antennas is defined by [2]:

$$BW = 3.77\frac{\varepsilon_r - 1}{\varepsilon_r^2}\frac{W}{L}\frac{t}{\lambda} \tag{5.4}$$

where ε_r is the relative permittivity of the dielectric, W and L are the path width and length, respectively; and t is the thickness. From the above equation we see that increasing the thickness increases the bandwidth, and lower dielectrics are better for wider bandwidths.

5.3.5 *Power Flow and Antenna Polarization*

One way to characterize the effectiveness of an antenna is to compare its physical size, while considering power radiated from and to the antenna. The correlation between power, orientation, and polarization can be shown from the Poynting vector relationship, where the average power flow (from an antenna oriented along the x-axis generating a linearly polarized E-field as shown below) can be expressed in the form:

$$S_{av} = \frac{1}{2}\left|E_x\right|^2\frac{1}{Z_0} = \frac{1}{2}\left|H_y\right|^2 Z_0 \tag{5.5}$$

Where S_{av} is the mean power density, Z_0 is the free-space impedance, E_x is electric field polarized along the x-axis, and H_x is the magnetic field with y-axis polarization. Now let us examine the two receiving antennas, one vertically polarized and the other horizontally polarized. Given the orientation of the transmitting antenna, the vertically polarized antenna will be more effective in absorbing the power from the free-space wavefield. However, from the RFID design robustness viewpoint, polarization diversity is important as the tags orientation, and thus the relative field polarization, might be undetermined in many applications as shown in Fig. 5.4.

5.3.6 *Antenna Arrays and Beam Pattern*

Properly spaced ultra-wideband antenna arrays can provide localized energy in both space and time. This technique is called “spotforming” and can be very effective in powering passive RFID tags from a long distance. Before starting our discussion on UWB spotforming in Sect. 5.3.7, it’s useful to discuss antenna arrays first.

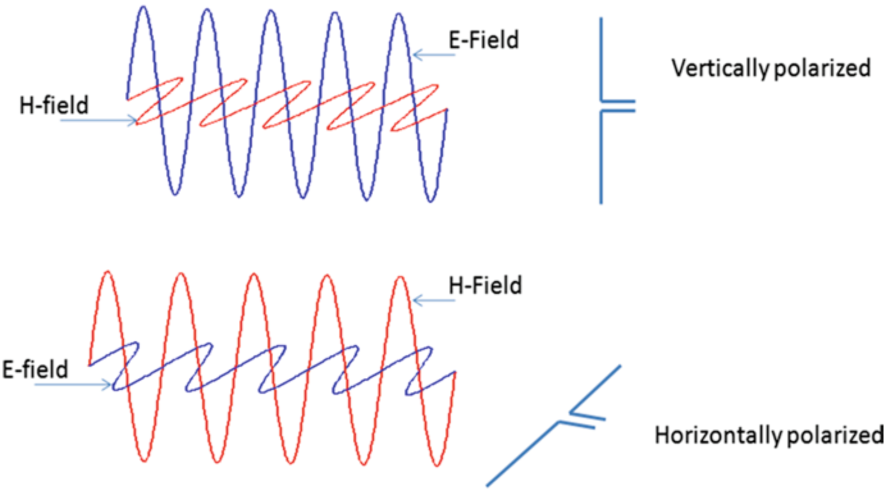

Fig. 5.4 When the receiving antennas are polarized in the same orientation as the transmitting antennas, the received power is optimized. Hence, polarization diversity for the tag reader antennas is a useful design feature

The "array" is a spatially distributed set of "antennas", where the geometrical arrangement of the antennas, and their excitation sequence result in a "multi-element array radiation pattern" which is different from the "single-element antenna radiation pattern". Therefore, antenna arrays lead to a more robust and diverse signal source, as they employ multiple antennas in multiple configurations. In this section we discuss some well-known characteristics of array beam patterns in terms of array aperture length and number of elements in the array.

What is the total field pattern of an array given each element has an antenna pattern? For a set of non-isotropic but identical elemental antenna pattern, the combined antenna array pattern is the product of the individual antenna source pattern and the pattern of an array of isotropic point sources assuming same array geometry. This can be argued mathematically using the time-domain convolution theorem[1]. The array pattern is a wave number response and therefore multiplicative. Figure 5.5 is a pictorial illustration of the total array pattern being the product of the single antenna beam patterns.

As shown by the (5.6) and Fig. 5.5, we note that in order to design an array with a certain beam pattern, the array radiation pattern is the same as beam pattern in signal array processing, and the analysis is identical to a plane wave impinging sensor array with delay-sum processing of the received signals. Typically, the array is in far field and the antenna elements are assumed to be identical, for example, the antennas in an array could be a set of dipoles. An in depth discussion of antennas or

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[1] Time domain convolution associates the output of a linear, time-invariant system, $y(t)$, to its input, $x(t)$, and channel impulse response, $h(t)$, by $y(t) = x(t) * h(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)\, d\tau$, where τ is a variable for time offset.

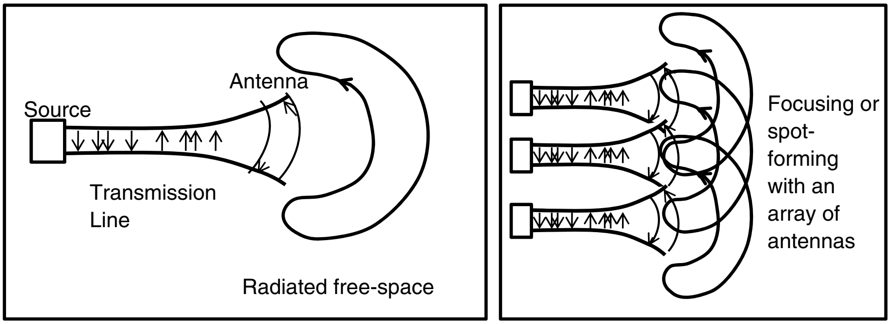

Fig. 5.5 The total array pattern is the product the array pattern of (**a**) the single antenna and (**b**) the array of isotropic antennas assuming all the antenna elements are identical

arrays require knowledge of EM antenna analysis as treated in classical antenna design texts [1]. Here we discuss this topic with a set of simple examples.

Consider first just the array pattern for a set of antenna receivers (or transmitters) on a linear space, as shown in Fig. 5.6, and consider three arrays:

- Array-1: A 5-element linear array with one-half wavelength inter-element spacing;
- Array-2: A 5-element linear array with a inter-element spacing of one-fourth wavelength spacing;
- Array-3: A 3-element array with an inter-element spacing of one-half wavelength. Note that the aperture (length of the array measured in wavelengths) is the same for Array-2 and Array-3, and the aperture of Array-1 is two times that of Array-2 and Array-3.

The examples illustrated in Fig. 5.6 shows that for high-resolution or high-directivity, the important term is the array aperture, as long as spatial aliasing is avoided. The number of elements in the array determines the array gain assuming uncorrelated noise among the antenna nodes, furthermore, a sparse antenna will have higher side lobes.

5.3.7 UWB Spotforming for Remote Powering

Ultra-wideband signals can be focused in space and time to form a spot in a distant location using a set of distributed transmitters. In order to form a spot with high signal to noise ratio in a distant location, all elements of the distributed UWB transmitters (array of antennas) have to transmit the same form of UWB pulse. The coherent addition of the pulses can generate a strong signal with high SNR that can be used to remotely power a passive UWB tag from a long distance. Increasing the number of elements in the array of transmitters improves the spotforming in terms of peak amplitude of the spot, signal-to-noise-ratio (SNR), and range [6, 7].

Fig. 5.6 Comparison of the array pattern of three different arrays, (**a**) and (**c**) with the same aperture (one-wavelength), and (**a**) and (**b**) with the same number of elements

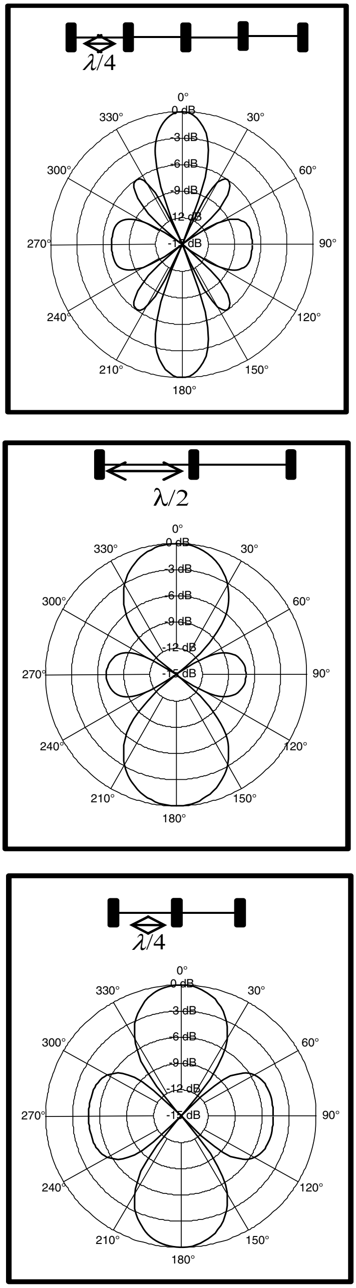

Figure 5.7 illustrates the concept of using UWB antenna arrays for forming a spot in a specific point in the far field of individual array elements.

The parameters that can be used to reduce the spot size and from a localized high energy signal at a distant spot are pulse shape and distance between the antenna

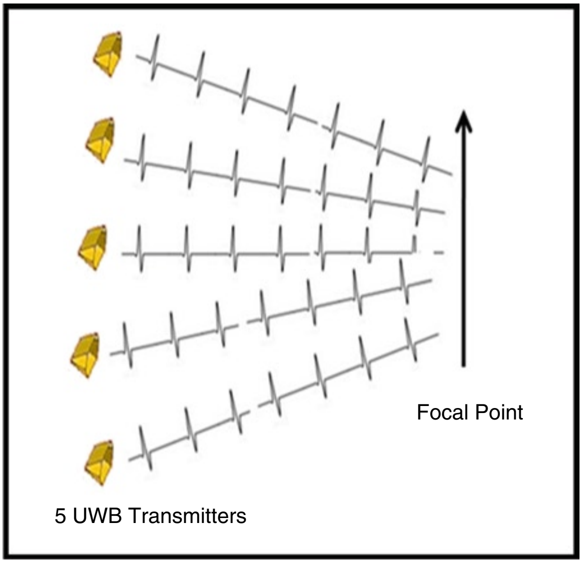

Fig. 5.7 UWB "spotforming" can localize the energy transferred from multiple antenna elements to a focal point of interest in both space and time

elements in the array (could be uniform or non-uniform separation). Various antenna array architectures for spotforming have been explored in [7] where sharper spots are reported for crossbeam arrangements compared to linear array and triangular arrangements. Designing an efficient spot in terms of peak amplitude, distance from the array, and sharpness of the spot can significantly improve the powering range of UWB passive tags.

5.4 Antennas for UWB RFID Tags[2]

In this section we consider the antenna design options for UWB RFID tags. Although the antenna design techniques for the near-field based passive tags have been developed to a fair degree of maturity, the short read range that they offer limit their use in many applications. On the other hand, most narrowband passive RFID systems with relatively long read range in the far-field operate in the VHF/UHF region of the spectrum. With the relatively long VHF/UHF wavelengths, the antenna design problem is limited by the larger size of the antenna. This is not the case for UWB antenna design because the UWB waveform has both low and high frequencies, and the 3D antenna shape provides many degrees of freedom for effective small size antennas. This section focuses on a number of different UWB antennas with an emphasis on their suitability for RFID tags.

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[2] Sections 5.4 to 5.6 are provided and courtesy of Dr. Vishwananth Iyer and Prof. Sergey Makarov of WPI.

5.4.1 Overview of UWB Antennas

A typical narrowband antenna design problem can be viewed in terms of the gain, bandwidth, polarization, etc. While these parameters are also critical to a UWB antenna, they are not sufficient. A UWB antenna also demands a stable phase center, which basically translates to a dispersion-free waveform being radiated. Furthermore, the radiation pattern needs to be stable across the wide bandwidth it is operating on. In this section we present a brief survey of UWB antennas and attempt to identify the potential candidate of choice for UWB based RFID tags.

Generally speaking, UWB antennas, in the context of RF tags, can be broadly classified into the following categories:

- Conventional broadband or frequency independent antennas (e.g. spiral and log-periodic; the large size of such antennas make them unattractive for RF tag applications).
- 2-D UWB patch antennas (e.g. small form factor antennas, such as bowtie, rectangular, triangular, slots, etc.; these antennas are suitable for tags and readers).
- 3-D UWB antennas (e.g. horns and cones; these antennas might be suitable for UWB tag readers, but not quite for tags.)

Frequency independent antennas exploit either geometrical '*angle*' or '*self similarity*' to achieve broad bandwidths. Therefore, the antenna structure can be divided into small, intermediate and large scale regions. These antennas theoretically do not possess an upper limit to their frequency of operation and hence their low frequency cut-off limit serves as the distinguishing factor. Obviously, the large scale region of the antennas defines this lower frequency limit. Common examples of conventional frequency independent, or "broadband" antennas are the spiral [8] and log-periodic [9] antennas, as shown in Fig. 5.8. These conventional broadband antennas are generally large. A modern version of frequency-independent design, are the fractal antennas discussed in [10].

While frequency independent antennas are capable of wide bandwidths, from a UWB RF tag system design point of view, they are not practical. Besides their large size and the waveform dispersion [10] features (i.e. non-linear phase response over the bandwidth) of these antennas make them unsuitable for UWB applications.

2D UWB Patch Antennas are built around the principle of ideal Hertzian electric and magnetic dipoles. Such antennas are widely used and possess several attractive features from a UWB tag perspective. Three key constraints they satisfy are that they can be of a small size, conformal in shape, and are non-dispersive [10]. In addition to these advantages, they also possess wide beam radiation pattern. Examples of such antennas include bowties and microstrip patch [9], slots [10] antennas. Figure 5.9 shows example of a UWB bow-tie antenna.

3D UWB antennas such as the horn or discone antennas are usually high-gain and with somewhat directional beam pattern and find widespread usage at microwave frequencies. They are commonly used as feeds for reflectors, in phased arrays and for calibration purposes. Horn antennas tend to have directional radiation patterns and high gain at the cost of being large bulky and more expensive. However, the planar horns such as Vivaldi antenna can be compact and inexpensive to fabricate [11]. These antennas have

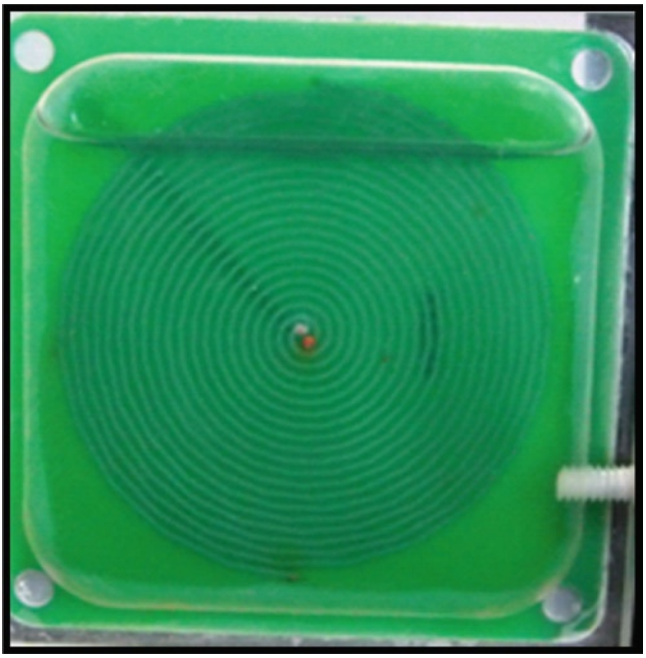


Fig. 5.8 Example of a spiral antenna

Fig. 5.9 Example of 2D UWB bow-tie antenna

close to linear phase response and therefore do not contribute to waveform dispersion and ringing as long as the feed is carefully designed in order to provide good impedance characteristics over the desired bandwidth of operation Fig. 5.10.

It is clear from the preceding sections that several choices exist for UWB antennas. However, to be used in an RFID system as a tag, the most significant attribute that the UWB antenna must possess is its ability to be integrated or embedded [12]. With this constraint, the field of potential candidates for a UWB based RFID tag antenna can be whittled down to a specific category, namely the planar printed antennas. This is primarily because such designs can be easily manufactured on printed circuit boards including FR4, and Rogers RT Duroid, or on other dielectric substrates such as Low Temperature Co-fired Ceramic (LTCC), paper, or even textile materials. Additionally, it could potentially ensure the widespread dissemination and acceptance of UWB based RFID systems by exploiting the technology available for PCB design, which is a mature field by itself.

In the next section, we present a discussion on a selection of planar printed antennas along with their defining characteristics that could be used in RFID tags.

5.4.2 Design Characteristics of the Planar Monopole/Dipole Antennas

The dipole or its counterpart, the monopole over an infinite ground plane, is one of the oldest, widely used and well researched class of antennas. So it is befitting that when considering antennas for UWB RFID systems, it is a strong contender. The major difference between the typical monopole/dipole antennas and the planar printed monopole/dipoles is the presence of the dielectric substrate. The presence of this dielectric is for the major part dictated by the need for the RFID tag to have embedded antennas. As a consequence, there is a conscious effort to keep the antenna on the PCB or any other dielectric material (e.g.: paper), depending on the application.

Traditionally, the cylindrical dipole or monopole over an infinite ground plane displays a narrow impedance bandwidth. As suggested in [13] the bandwidth could be increased if the antenna occupies a larger volume. It is this point which allows us to understand the reason for the narrowband properties of a typical wire (or blade) dipole or monopole antennas. It's important to note that the total length of this dipole is set by its resonant frequency. As shown in Fig. 5.11, if we now imagine the dipole is enclosed in an imaginary sphere of radius, 'a' which is equal to the half length of the dipole, it becomes obvious that the fractional volume occupied by the linear (cylindrical) structure is very small compared to the volume of this sphere.

A classic technique to increase the bandwidth is to make the dipole substantially thicker and to flare it into a biconical shape or to taper it [14]. Both of these approaches result in a larger fractional volume being occupied and result in higher realized bandwidths. To increase the bandwidth even more, a geometric shape such as the hemisphere can be used instead. This effectively fills up most of the volume of the enclosing sphere. For the monopole, one of the sections of the biconical, tapered and hemispherical dipole configurations is replaced with an infinite ground plane.

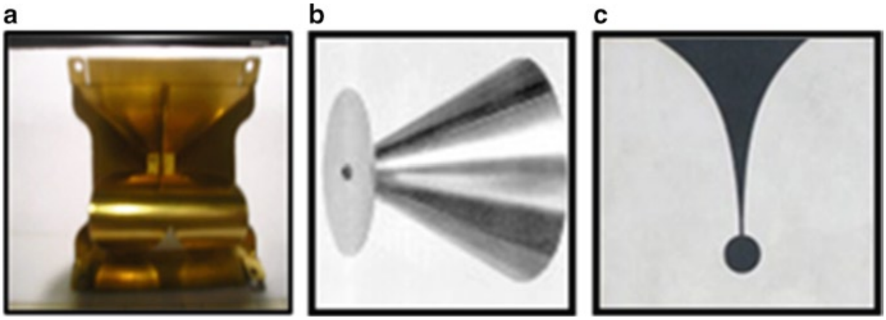
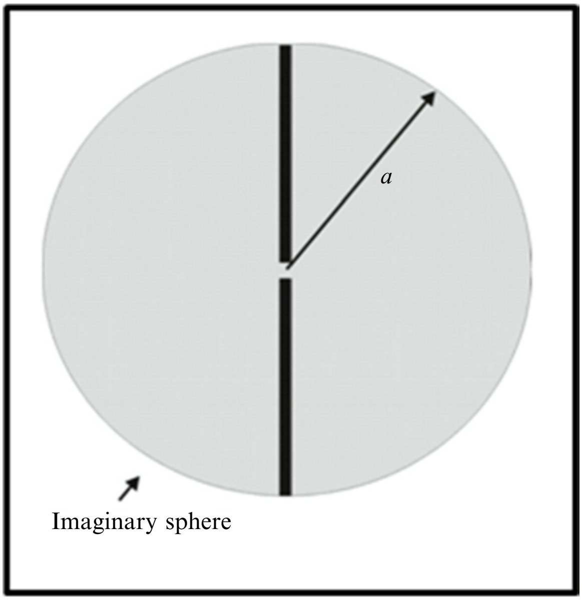


Fig. 5.10 Example of (**a**) horn antenna, (**b**) discone antenna, and (**c**) vivaldi antenna representation

Fig. 5.11 Dipole enclosed within imaginary sphere



From a UWB perspective these antennas have an omni-directional radiation pattern and are non-dispersive, i.e. they display a stable phase center. While this is an effective technique in increasing the bandwidth, it is not very practical in terms of implementation, specifically for UWB tags. Therefore we consider the planar version of these classical configurations. Taking biconical configuration, its planar version is the bow-tie antenna. Similar flat structures can be realized for the tapered as well as the hemispherical configuration and be readily integrated onto PCB's to serve as the antenna. Figure 5.12 shows some of the typical configurations of such antennas. Depending upon the type of design, one could choose the monopole version of these antennas. In such a case an adequately large ground plane, would be required.

Inspired by these designs, the following two interesting candidates for a planar antenna are introduced here:

- Planar Inverted Cone Antenna (PICA),
- Petaloid Antenna.

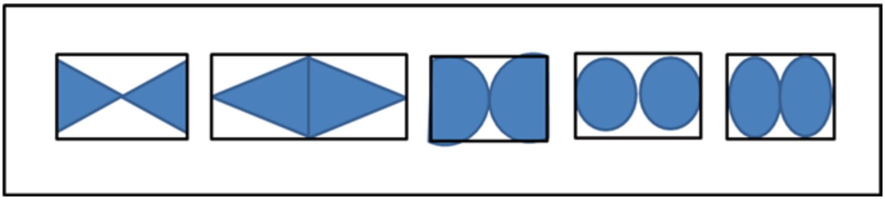


Fig. 5.12 Typical choices for planar antennas, bowtie, diamond, half circle, circular, elliptical [10]

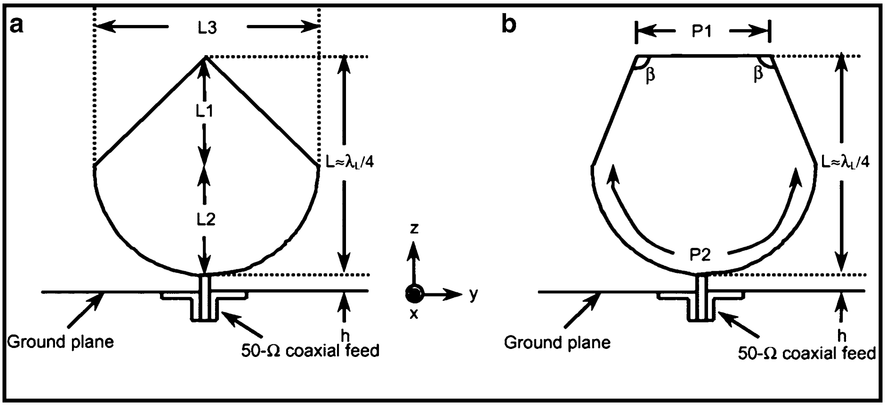


Fig. 5.13 Geometries of (**a**) Basic and (**b**) General PICAantennas. (Source [15], © 2004 IEEE)

Planar Inverted Cone Antenna (PICA) – The PICA possesses similar properties to the monopole version of the antennas shown in Fig. 5.13, specifically the circular disk like shape and yet is smaller in size.

The Fig. 5.13, shows the typical configurations reported in [15]. This antenna, as reported, provides a 10:1 impedance bandwidth and has an unbalanced feed. Important design parameters to be optimized for the basic PICA are L_1, L_2, and L_3 where the fundamental dimension L is set to be λ/4. Variations of this antenna were also suggested in [15] to improve the matching performance and the radiation pattern at higher frequencies.

Petaloid Antenna – This particular configuration was reported in [16] for passive UWB RFID tags. The passive nature of the tag means that special attention has been devoted to the scattering properties of this antenna since it was desired that a chip-less implementation be targeted. The backscatter from this antenna can be divided into a structural mode and an antenna mode, out of which special attention has been paid to the antenna mode so as to realize an omni-directional pattern. As stated earlier, the design is inspired from planar circular-disc monopole antennas. The substrate is FR4 and the feed line width is optimized to provide a 50 Ω match across the requisite bandwidth.

The Petaloid antenna is compact in size and low cost to fabricate with omni-directional in pattern which all are characteristics that are desirable for UWB passive tags.

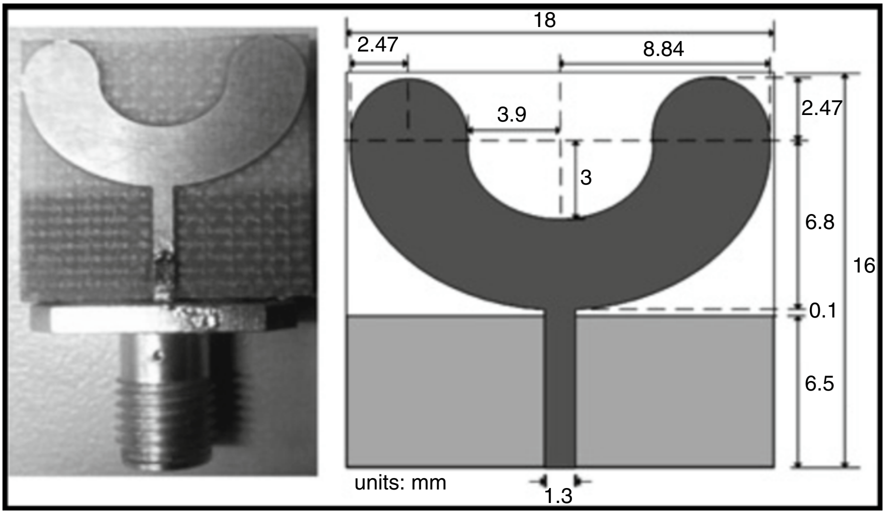


Fig. 5.14 Fabricated petaloid antenna with details of all critical design parameters. (Source [14], © 2007 IEEE)

5.4.3 Patch Antennas

The microstrip patch antenna is a widely studied class of antennas and does have desirable properties such as omni-directional pattern and being non-dispersive to the applied waveform. The traditional microstrip patch antenna comprises a rectangular metal sheet with critical dimensions *W* and *L* over a ground plane and separated by a dielectric such as foam, FR4 etc. The basic patch antenna is usually narrowband with fractional bandwidths of 5–15%. Several design techniques have been reported which enhance the bandwidth significantly for their use in UWB tags.

One approach to increase the bandwidth of the microstrip patch antennas for use in UWB tags is to modify the feedline by incorporating steps into it and by introducing a slot within the region of the rectangular patch. By controlling the step widths and the size of the rectangular slot as shown in Fig. 5.15 [17], an impedance bandwidth of 3.2–12 GHz was reported. This design also featured a restricted ground plane as compared to the size of the substrate. The price paid was in terms of its radiation pattern which was reported to be quasi-omni-directional. On a different note, a planar microstrip UWB antenna design was reported in [18], which is fed using a co-planar waveguide (CPW). The unique feature of this antenna was its ability to provide a frequency band notch at any particular frequency by varying the length of the V-shaped notch. This design is small in size and provides bandwidth ranging from 2.8 GHz to 10.6 GHz. As shown in Fig. 5.15, the important design variables are – *a, b*, which represent the overall size of the structure including the substrate and the antenna, feed line parameters *g*, *w*, and length of the V-shaped slot *L*.

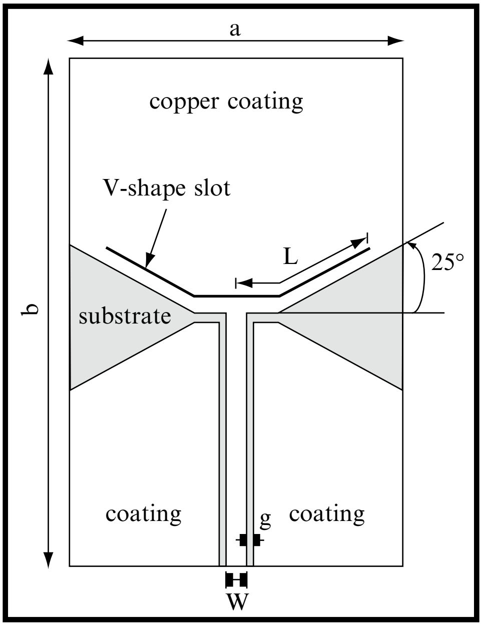


Fig. 5.15 A CPW fed planar antenna with frequency bandn notch function. (Source [18], © 2004 IEEE)

5.5 Antennas for Wearable UWB RFID Tags

UWB RFID tags can play an important role in the field of wearable computing and the associated paradigm of a wireless body area network (WBAN). This emerging technology area poses the following set of design requirements on the antennas:

- Antennas have to be integrated into the clothing (textile)
- Antennas will be part of the garment and hence should be flexible enough to tolerate moderate levels of deformation
- Proximity to the human body at all times requires that such antennas work with limited amount of radiated power

The fact that UWB systems use low power transmission levels makes them good candidates for wearable RFID tags. Thus, most of the UWB antenna requirements discussed in earlier sections such as omni-directional pattern, small size, and conformal design are also applicable to the wearable UWB based RFID tags. In the next two subsections, we provide a general overview of textile antennas that have been reported in the literature, and will focus summarizing the results of a report on UWB textile antennas.

5.5.1 *Textile Antennas*

A great amount of research that has been reported in textile antennas was focused on applications for the wireless local area network (WLAN). As noted in [19],

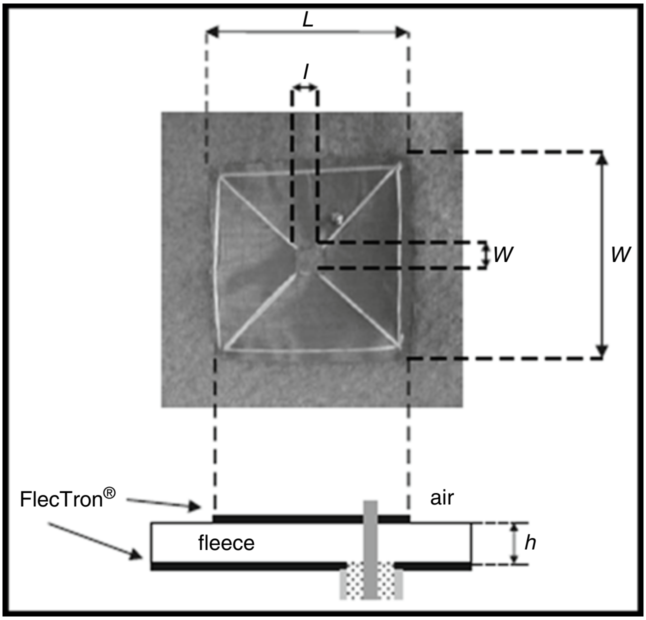


Fig. 5.16 Geometry of rectangular-ring microstrip textile antenna. (Source [22], © 2006 IEEE)

the effect of the conductive textile material is significant in the performance of any textile antenna. A comparison of different WLAN antennas manufactured using conductive materials such as knitted copper, copper tape, aracon fabric etc., on fleece fabric for operation around the 2.45 GHz is reported. It was concluded in [19] that discontinuities perpendicular to the current flow should be avoided and that a dense knitting of the underlying fabric along with a suitable conductive material would result in high performance.

In [20, 21] a planar textile antenna design was reported for use in the 2.45 GHz ISM band. Similar to [19], the non conductive substrate is fleece while the conductive layer of the antenna is made out of copper plated nylon woven fabric, referred to as FlecTron® fabric [22]. This fabric is light in weight, can be easily cut, sewn and has low surface resistivity (< 0.1 Ω/sq.). The antenna chosen is a single feed planar rectangular-ring antenna and is shown in Fig. 5.16. As is typical, the geometry of the patch and the feed point location are optimized to obtain a return loss of < -10dB over the band 2.4–2.483 GHz. The results reported suggest robust performance to deformation and efficiencies of higher than 70%.

The effect of human body on the textile antenna is analyzed in some detail in [21]. A log-periodic folded dipole array antenna is suggested as a good choice for the antenna configuration and design equations are provided. Measurement results for prototype antennas in the 868 MHz band and the 2.4 GHz bands are provided. While the 868 MHz antenna is made out of copper tape, the 2.4 GHz antenna is built by embroidering into the fabric by stainless steel fibers. An interesting feature

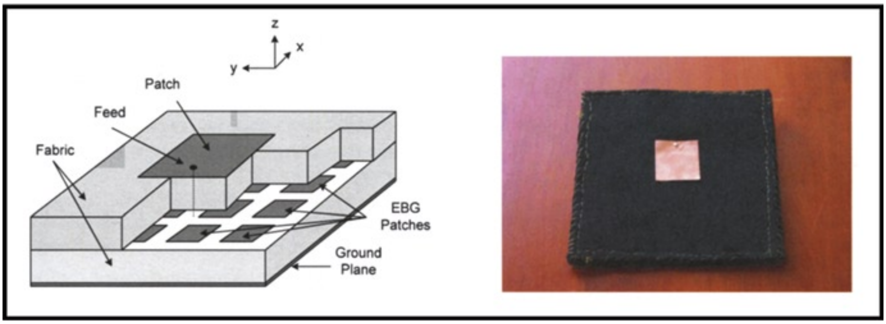


Fig. 5.17 Wearable EBG antenna geometry (*left*) and the prototype (*right*). (Source [24], © 2008 IEEE)

of these antennas is that unlike the designs mentioned earlier in [19, 20, 22], the conductive material is a commonly available material such as copper, stainless steel and the substrate material is regular cotton.

Along with weaving, embroidering and use of foils of copper or other conductive materials that are directly applied to the fabric substrate, there are two other techniques to incorporate the conductive material onto the fabric. As explained in [21], a conductive spray consisting of copper along with pressurized gases can be used to basically spray the antenna onto the fabric. Also, a mixture of conductive nanoparticles of (for e.g. copper) along with rubber can be used to produce textile antennas and other electronics [23]. The effects of deformation of the textile antenna on the resonant frequency and the impedance bandwidth are conveyed in [24, 25]. The antennas used for the study were a conventional patch antenna, an electromagnetic band gap (EBG) antenna and a dual band antenna (U-slot) Fig. 5.17.

The results, which are relevant for all three antennas, suggest that deformation along the resonant length of the antenna causes the most changes to the resonant frequency and the impedance bandwidth.

5.5.2 Textile UWB Antenna

The development of a textile antenna was reported in [26] for operation over the UWB band of 3.1–10.6 GHz. This textile antenna uses a metalized form of nylon as the conductor while acrylic is the dielectric substrate. The conductor has three layers consisting of nickel, copper, and silver. Attachment of the conductive layers to the substrate is done through the use of special adhesives which provide a good solution to this critical problem while ensuring that the electrical properties of the textile materials are not modified. Two alternatives are considered for the choice of the antenna such that a low profile and small size could be realized. These were namely, *the CPW fed disc monopole* and *the microstrip fed annular slot* which are shown in Fig. 5.18.

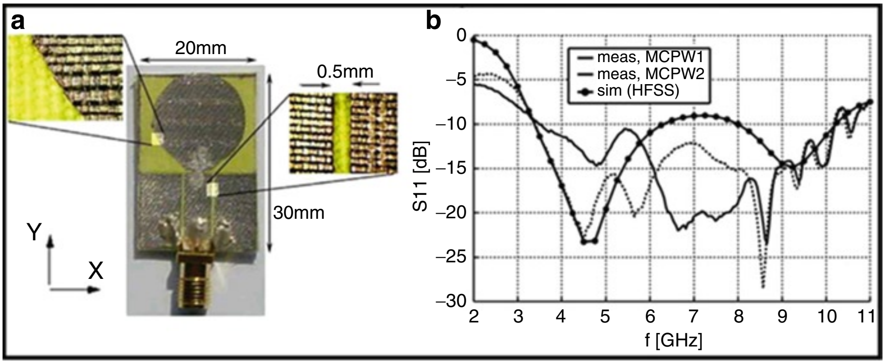


Fig. 5.18 CPW-fed textile UWB disc monopole antenna: (**a**) photograph and (**b**) measured and simulated return loss characteristics. MCPW1, MCPW2: two prototypes of this textile antenna. (Source [25], © 2006 IEEE)

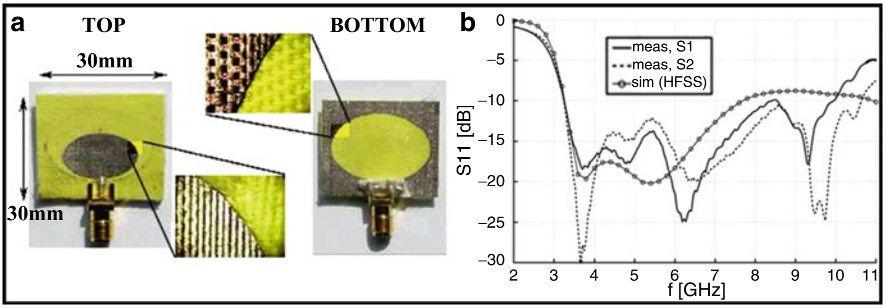


Fig. 5.19 Microsrip-fed textile UWB annular slot antenna: (**a**) photograph and (**b**) measured and simulated return loss characteristics. S1, S2: two prototypes of this textile antenna. (Source [25], © 2006 IEEE)

In general, the precision required during the manufacturing process for both these antennas is limited by the fact that only simple tools (such as a scalpel) could be used. In addition the dimensions of the antennas could not be cut to the exact values as required by calculation. The feed in both cases is designed to provide a 50 Ω match over the impedance bandwidth of 3.1–10.6 GHz Fig. 5.19.

5.6 Impedance Matching and On-Chip Antennas

The various types of UWB antennas which were reviewed in earlier sections would be of little use if not for impedance matching. Impedance matching is required to transfer power from the source to the load (antenna) effectively. Typically impedance matching is viewed from the perspective of conjugate

Fig. 5.20 Representation of a UWB vivaldi antenna

matching which allows for maximum power transfer to occur at a single frequency. This technique can be implemented either by using lumped components at VHF frequencies or through distributed elements at UHF frequencies and above as discussed in [27], [28]. However, this approach is narrowband. Although the bandwidth can be increased by using the Q based approach [29] or by using reflective equalizers [30], it still cannot provide the total bandwidths required for UWB systems such as 2:1, 5:1 etc.

5.6.1 UWB Antenna Feed Design: Key to Impedance Matching

To achieve the several octaves of bandwidth required in UWB systems, an approach to impedance matching involves proper choice of antenna shape and feed design. In general the source has an impedance of 50 Ω. The challenge is to transition from the antenna to the feed point so as to present impedance as close to the 50 Ω requirement across the entire band. We consider the following two examples to illustrate this point:

- Slot Coupled Vivaldi Antenna
- UWB Patch Antenna

5.6.1.1 Slot Coupled Vivaldi Antenna

In the slot coupled Vivaldi antenna a combination of stripline and slotline are used to feed the antenna. On the top surface of the antenna the exponential taper encounters a circular shaped cavity that acts like an open circuit Fig. 5.20.

As shown in Fig. 5.20, the tapered feed line on the bottom is shorted using a stripline stub. The gradual taper on the antenna together with the feed design provide a controlled impedance match and thereby ensure broadband operation.

5.6.1.2 UWB Patch Antenna

The UWB antenna reported in [17] is based on the conventional patch antenna. Whilst the patch antenna is narrowband, some modifications to its structure and to the feeding arrangement allow for ultra-wideband operation. The shape of the reported patch antenna is rectangular and a slot has been introduced within the patch surface to modify its impedance characteristics. In addition, the ground plane has been curtailed. A stepped impedance transformation comprising of two steps is used to transition from the microstrip line to the patch and thereby achieve the impedance match.

5.6.2 On-Chip Antennas

There is growing interest in realizing a complete RF transceiver within a single chip in RFID and sensor network systems. The idea of having a System-on-Chip (SoC) has many desirable characteristics, such as smaller size, economic feasibility and increased reliability [30]. Since the antenna is located off chip an important step in successfully designing the SoC is in integrating the antenna onto the chip. Several frequency ranges are being researched and reported in the literature. The traditional 3–5 GHz and the 6–10 GHz are an obvious choice for SoC solutions. The 24 GHz, 57–64 GHz, and the 77–81 GHz band are all actively being researched as well [29]. The small wavelengths in these bands make it attractive for an on-chip antenna solution. Additionally the presence of a dielectric substrate (commonly silicon) would result in further shrinking of the wavelength and would help in miniaturization of the antenna. However the losses in the substrate together with higher absorption of power due to possible high dielectric permittivity are potential problems that have to be dealt with [32]. Two techniques that are employed to achieve integration are covered in the next two sections. The first technique is based on using bulk silicon itself as the substrate for making an on-chip-antenna. The second technique utilizes the Low temperature co-fired ceramic (LTCC) technology as the substrate.

5.6.3 Bulk Si Based On-Chip Antennas

To implement a single chip radio, one obvious alternative to the external antenna is to embed it onto the bulk silicon substrate within the chip. Typically, the CMOS technology utilizes substrates of resistivity in the range $10\,\Omega$ - cm to $20\,\Omega$ - cm. Since the technology for IC design and manufacturing is mature, it is expected that an on-chip-antenna would be inexpensive to realize and can be produced in large quantities. The choice of antennas in this regard is restricted to the dipoles, monopoles and their variations due to the space conserving features. The dipole, if chosen, requires a balun whereas for a monopole and its variations, a ground plane is required, which can be provided through the substrate [30]. Two key challenges to tackle are

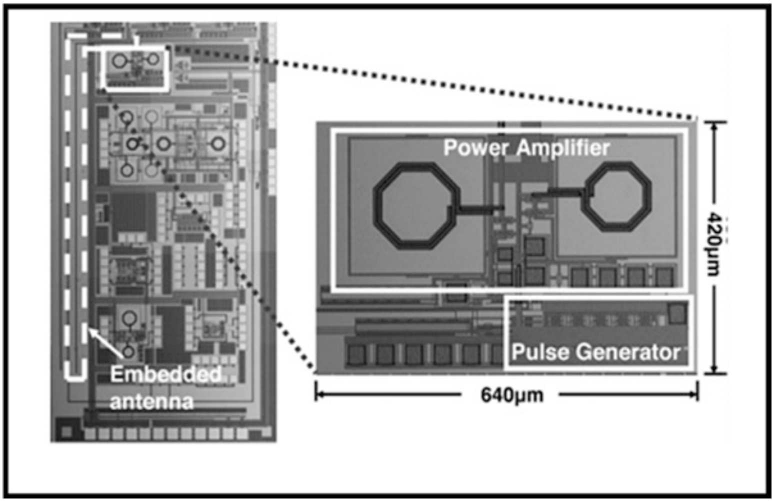


Fig. 5.21 On-chip antenna with the power amplifier circuitry. (Source [30], © 2009 IEEE)

low efficiency due to the lossy substrate and the effect of metal surfaces and layers close to the antenna structure. Figure 5.21 shows an implementation of an on-chip-antenna for Impulse radio UWB. The operating bandwidth for this system is 6–10 GHz. The monopole was chosen since it has a single-ended input compatible for the desired application and for the fact that its size is smaller compared to a dipole [30]. In addition, since the antenna will be located on the silicon substrate, a further shortening of its length can be achieved. In this design, a power amplifier is used prior to the antenna to overcome losses in the substrate.

5.6.4 Low Temperature Co-fired Ceramic (LTCC) Technology

The single package solution is not exactly the SoC realization, but nevertheless represents an important advancement towards this final goal. In such solutions, the UWB transceiver chip and the UWB antenna are brought together on the LTCC package [26]. LTCC technology has several benefits such as thermal stability, good electrical properties, low cost, and excellent reliability. In [31] and [32], the authors propose the use of LTCC technology in implementing the single package solution. The antenna design procedure can be broadly split up into two steps, namely choice of antenna structure and the design of the feed. The UWB integrated package antenna proposed in [32], an antenna has been designed for operation in the 5.5–10.6 GHz band. The design of this antenna is centered around optimizing the return loss so as to achieve −10dB across the band of interest. The design proceeds through several iterations which are discussed here.

The initial antenna design focuses on satisfying the return loss criterion. Upon integration into the package, the performance expectedly changes. To improve the

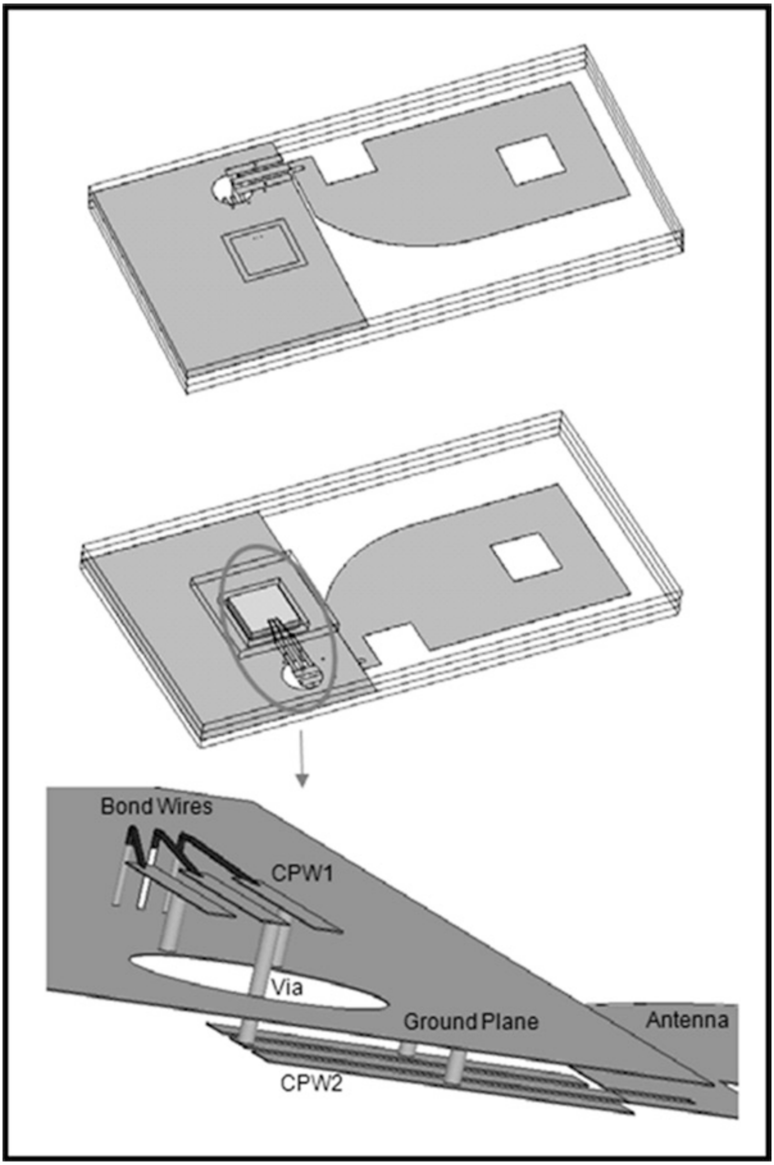


Fig. 5.22 (*Top*) Integrated UWB antenna in LTCC, (*bottom*) feeding network highlighted. (Source [32], © 2006 IEEE)

integrated antenna performance, the antenna geometry is modified in accordance with the package shape and space constraints together with the return loss criterion. Having completed this, the feeding network is designed and optimized to ensure a good match to 50 Ω. The antenna and feed in the package are shown in Fig. 5.22.

The feeding network comprises gold bond wires connected to CPW's which carry the signal through a second set of CPW's which feed the antenna. The final step consists of characterizing the performance of the antenna with the feeding network.

5.7 Summary

In this chapter, we covered a range of fundamental and advanced topics related to antenna design issues of long range passive RFID systems. From the discussion in this chapter, a great amount of research has been undertaken to overcome the unique challenges that passive RFID systems present to the UWB antennas. These challenges have been addressed through a variety of solutions for both the reader and the passive tag antennas. The performance of UWB readers can be significantly improved by using multi-element antenna arrays to improve the effectiveness of remote powering techniques in forward link, and hence increasing the communications range of such systems. Efficient antenna design for UWB passive tags that result in compact, low cost, and omni-directional radiation pattern can address the challenges of UWB passive tags in terms of efficient back-scattering. UWB antennas can be implemented on flexible substrates to bring the advantages of UWB technology discussed in Chap. 4 to wearable RFID systems with all the benefits of added security and operational reliability. However, these challenges become increasingly complex for wearable antennas and SoC implementations and are still active areas of research.

The dipoles, monopoles and their variations continue to be popular choices as UWB antennas for RFID tags. Lastly, impedance matching remains as an important aspect to address for a successful implementation of a UWB antenna design in long range passive RFID systems.

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Chapter 6
RF Tags for Special Applications[1]

6.1 Introduction

In spite of the common notion that RFID is a technology for use primarily in departmental stores and supermarkets, the RFID technology might actually be most useful in a number of many special applications. In some of these applications, minimizing the cost of a tag might not necessarily be the main objective. There are a number of important problems where the performance of the tagging and tracking system, rather than a tag's unit cost, is the critical factor. Although newer generation UHF and LF tags can sometimes be adapted to achieve an acceptable level of performance, the UWB technology might be a natural solution in many other special applications. In this chapter we discuss applications areas where UWB RF tags have the potential to play an important role.

6.2 Monitoring of High Valued Items

There are many applications where items that need to be monitored have been referred to as "high-value" items. A common example might be precious and rare items in a museum. Other examples include special devices in nuclear treaty monitoring applications. The requirements, specifications, and costs for developing specialized RFID monitoring in such environments or facilities are quite different from the requirements of an RFID systems for instance in a local supermarket. Some of the general requirements for these applications are:

- Ability to interrogate reliably with respect to the environment
- Ability to operate for many years (i.e. without relying of battery lifetime)
- Ability to communicate with encryption and authentication

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- Allowing attachment to metal surfaces
- Ability to provide unique identifiers for multiple items
- Allowing long read range

Given the above list of requirements, UWB RF tagging technology can address a number of these requirements quite naturally. UWB allows robust communication because it has inherent frequency diversity. The passive and long read-range can also be addressed by UWB pulses using the spot forming capability of UWB signaling. Finally, UWB tags have been developed for attachment to metal surfaces. With respect to the other requirements (i.e., large number of unique identifiers, and authentication, encryption) most RF tags can be designed to have these capabilities. However, UWB tags with encryption capability can be designed with lower complexity as we discussed in Chap. 3.

There are many other applications such as inspection of cargo containers where the environment is similar: harsh, metallic, and difficult to access. Such tasks can be quite difficult for the inspectors. Hence, inspection automation using UWB RF tags is an important application area for many such specialized areas of operation. In conclusion, RF tags, and in particular UWB RF tags, can indeed play a useful role for the monitoring of high-value items.

6.3 Bio-Medical Sensor Systems

RF tags are applicable in a number of different problems in bio-medical applications. A wearable RF tag can be used in medical monitoring application, for example in the real-time monitoring of patient's vital signals. A tag integrated with medical sensors can be used to monitor a patient's vital signals such as temperature, heart rate, respiration, pulse-oximetry, EKG, EEG and other important bio-medical signals. In fact, the use of RF tags for wireless body area networks (WBAN) is a rapidly growing area. The use of passive and small tags is particularly attractive when the tag is attached to the body Fig. 6.1.

As shown in Fig. 6.1, a patients vital signals are being constantly monitored at a hospital. The RF tag/sensor is attached to the patient's body in her home and real-time data could be sent to the hospital through the internet access.

RF tags are particularly attractive because they can be designed to accommodate the functions of both sensors and transceivers. The sensor integrated with the tag will send the data only when interrogated. This reduces the power required to communicate with sensors. With small passive tags, the sensor can in fact be emplaced inside the body.

Another well-known and highly successful application of RF tags is the use of 13.56 MHz RF tags, developed for example by ClearCount Inc., to detect surgical sponges left in patients during surgeries. Surgical objects are sometimes accidently left behind inside patients during surgeries; blood-stained sponges being one of the most common objects, as they are easily camouflaged. A sponge that can be detected and removed is obviously an extremely useful tool for the surgical team.

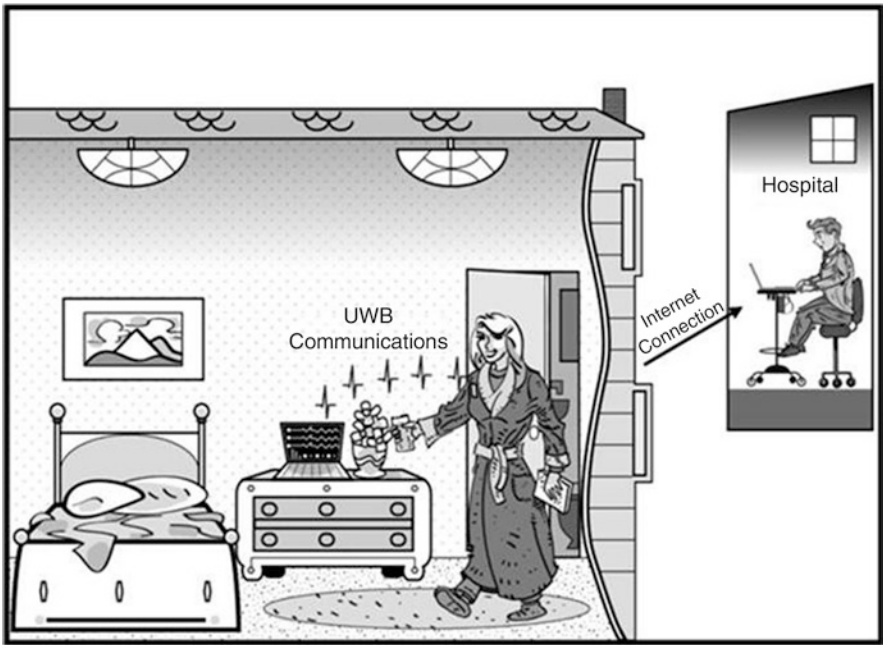

Fig. 6.1 RF tags for body area sensors

While a 13.56 MHz RF tag might be useful for the detection of surgical sponges, UWB RF tags might be important to detect metallic objects, such as scissors and retractors, in the surgery table. The inventory of surgical equipment before and during a surgery is a stressful task, one prone to human error. The use of RF tags for rapid and automated inventory of all types of surgical equipment can be quite useful. The requirements for this application are obvious – passive, robust performance, and small form factor – a case for high-frequency UWB tags shown in Fig. 6.2.

6.4 RF Tags for Ammunition Inventory

Munitions supplies are often tagged with 2D bar codes or active RFID tags to enable automatic monitoring of the ammunitions. Ideally, one would like these tags to be passive long-range tags, ones that work on metallic surfaces. Furthermore, the position or geo-location (x, y, and z coordinates of the room) of these objects is an important parameter. While reflections from metallic surfaces might create an uncertain RF environment for narrow band signals, for UWB signals reflections and multipath can be used to one's own advantage. These features of UWB tags, discussed in the earlier chapters, suggest that UWB tags might be appropriate for this application, where the location of the tags is an important information. Robotic tag readers with the capability to read RF tags might be the best solution for this enormously laborious inventory process Fig. 6.3.

Fig. 6.2 Tracking surgery equipment with RFID

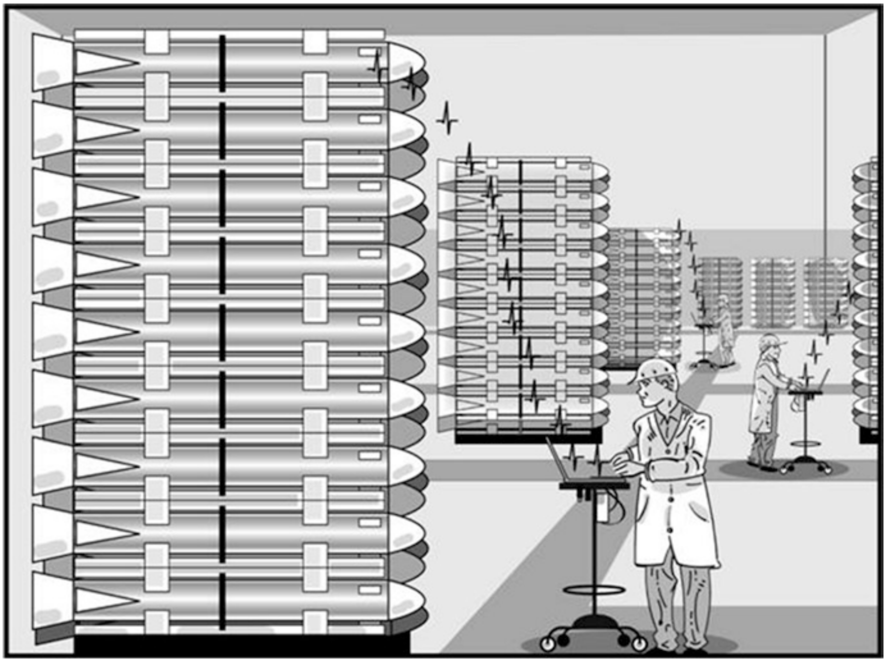

Fig. 6.3 Example of a warehouse for warfare depot

As shown in Fig. 6.3, RF tags are attached to each munitions and provide automatic inventory of the items. The pulse based transmission, is the key to reliable communications between tags and readers in such heavy metallic and cluttered environments.

6.5 Unexploded Ordnance (UXO) Detection

It is estimated that millions of acres of land have been lost to buried unexploded ordinances (UXO). While Ground Penetrating Radar (GPR) techniques can be used to detect and remove buried UXOs, this technique often has high false alarm rates because any buried conductive or reflective objects, including rocks, can show up as detections in a GPR image. Although a futuristic concept at the present time, passive UWB tags embedded on the skin of the ordinance shells, would allow a very high probability of detection on buried UXO's with a false alarm rate close to zero. Since only the tags can be identified by the readers through pulse communications, no other object (i.e. rocks) that can cause false alarm (Fig. 6.4).

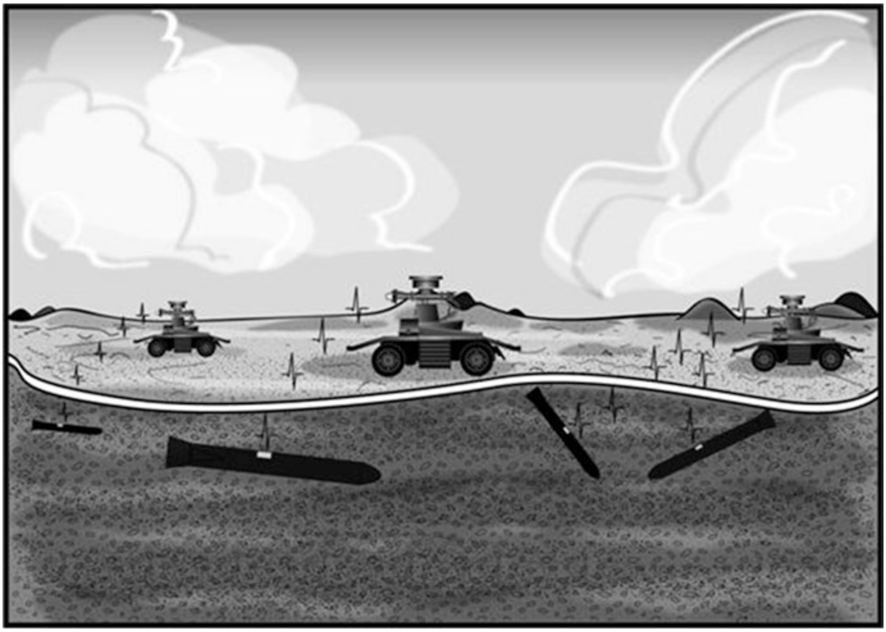

Fig. 6.4 UXO detection with UWB RF tags

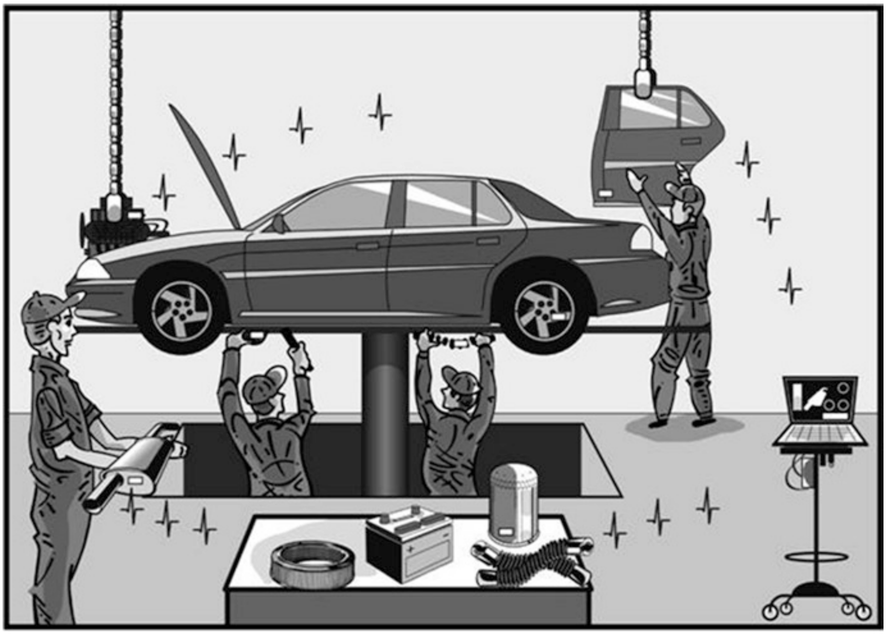

Fig. 6.5 Automobile assembly plant

6.6 Automotive Assembly

In automotive assembly lines, RFID technology has been used for the identification and tracking of assembled vehicles. For example, some automobile assembly plants emplace tags onto engines, chassis, bodies, seats, etc., in the assembly process to expedite and improve the quality of the work in assembling millions of cars. Once again, the number of metallic objects in such an environment is abundant and the use of passive RF tags that work on metals would be more widely applicable (Fig. 6.5).

6.7 Indoor Personnel Location and Tracking for Emergency Responders

The need to locate and track personnel for emergency responders, such as firefighters responding to an emergency incident, is problem of significant importance. Hundreds of lives are lost each year as responders conduct search and rescue attempts inside buildings on fire. The incident commander needs to precisely know the floor and the room of the first responders inside the buildings at all times. It turns out knowing which floors the responders are situated is one of the many parameters for the incident commander, however, *precise geolocation* of all personnel in real-time is a

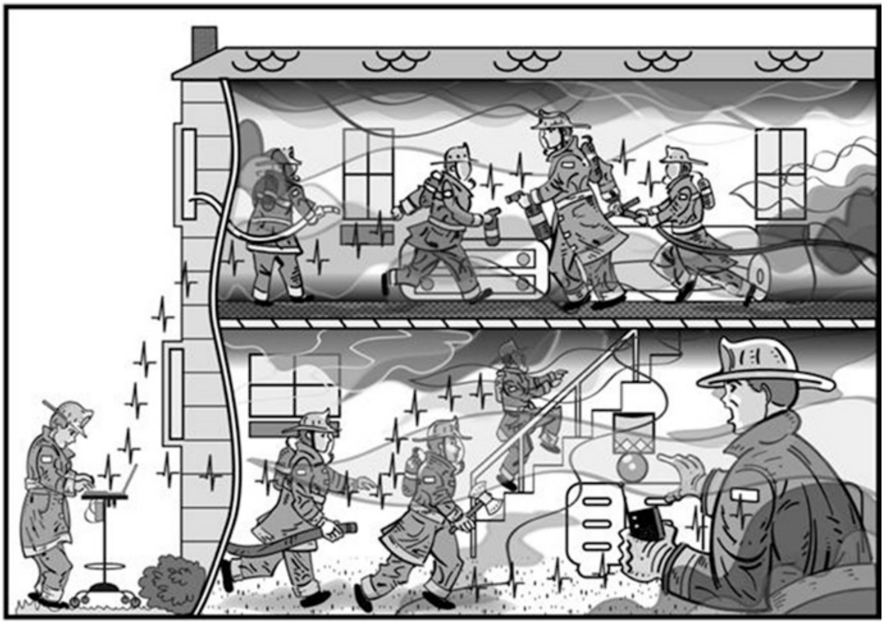

Fig. 6.6 Personnel locating and tracking with RF tags might be a critical technology for emergency responders (above figure is a place holder to be replaced by another). The use of RF tags and readers at various points in the building or on the responders it might be possible to develop a personnel geolocation system

critical need. In this application, the readers must be outside the building. Hence, a set of relatively long-range readers of RF tags, with the tags attached to the responders, might be the ultimate solution Fig. 6.6.

Because of the harsh indoor propagation environment of buildings, the use of UWB RF tags might be important for this problem. In fact, long-range RF tags might be the most useful solution to address this need. The ideal solution would consist of a passive tag that can be accurately detected from outside the building, however, for power limitations in this scenario, active UWB tags can play an important role.

6.8 Summary

The ability to extend the use of RF tags for both long-range applications and through harsh EM environments might lead to a number special application where RF tags will prove to be an invaluable technology. In this final chapter, we discussed only some of the special applications and clearly, there are many other such applications. In many of these applications the use of UWB RF technology for long-range passive tags operating in metallic environment is bound to play an important role in the near future. While passive tags have limitations in range, the use of active UWB tags can be an alternative due to the advantages that UWB signaling brings to RF tagging and tracking applications in hostile environments.

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Glossary

Active tag Active RFID tags/transponders require an onboard source of energy (battery) to power their communications. The active RFID communication model is no different than any other wireless communication system where transmitters (tags) communicate with receivers (readers) over a wireless link using radio waves. Active tags have long read ranges at the cost of being bulky, expensive, and having limited lifetime equal to their battery life.

ADC Stands for Analog-to-Digital Converter, an electronic device that converts analog (continuous) signals to digital (discrete) signals using sampling and quantization techniques.

Antenna An antenna is a conductive element that is responsible for the transmission and reception of free-space or through-barrier electromagnetic (EM) signals. In the context of RFID, tag antenna provides RF signal transfer by means of broadcasting the signals (active tags) or backscattering/reflecting the signals (passive tags). The reader antenna in an RFID system actively transmits and receives signals to/from tags.

Antenna directivity Fundamental antenna parameter that defines the level of intensity that an antenna radiates in a specific direction in the transmit mode and receive in the receive mode. This parameter shows the directionality of an antennas radiation pattern.

Antenna efficiency Antenna parameter that defines the ratio of the radiated power from an antenna to power input to the antenna.

Application software In the context of RFID, the application software is specialized computer software that is designed to translate the received data from RFID tag to user-friendly messages regarding the tagged item's location or its presence and absence status.

Backscatter Method for data transfer between a passive (batteryless) tag and its reader, where the tag modulates and reflects (backscatters) the reader signal to send its data.

Bandwidth Radio frequency bandwidth (measured in Hz) is defined as the range of frequencies in the electromagnetic spectrum that a communication system is

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able to transmit and receive. Data bandwidth (measured in bits/sec) is defined as the amount of data that a communication system can transmit and receive.

Barcode Method for representing data by using a unique sequence of vertical lines that is readable by an optical scanner.

Baseband signal A baseband RF signal or impulse radio does not have a specific carrier frequency (carrierless) and can cover a large range of frequencies from near "0" Hz to several GHz.

Bipolar transistor A bipolar transistor is a semiconductor device formed by two P-N junctions and is used for amplification or switching of analog or digital signals in a circuit.

Capacitor An electric component that consists of two conductive plates separated by an insulator (dielectric) and is used for temporary storage of electric charge.

Channel Capacity translate the received data to user-friendly messages regarding the tagged item's location or its presence and absence status.

Carrier Frequency Specific frequency that is used to modulate data in narrowband signal transmission.

Carrierless signal Refer to baseband signal.

CEPT Stands for Conference European Posts and Telegraphs regional organization that is responsible for regulatory issues of European RF spectrum.

Chirp signal Chirp or sweep is a sinusoidal signal that its frequency continuously increases or decreases with time.

Class 0 tags Refers to simple passive identity tags that use backscattering technology for their tag-to-reader communications (reverse link).

Class 1 tags Refers to passive, read only ID tags that can be written once by their users.

Class 2 tags Refers to higher functionality passive tags with extended memory and read/write as well as authentication and encryption capabilities.

Class 3 tags **Refers to** semi-passive or battery assisted passive (BAP) tags at UHF frequencies that have a power source to operate their internal circuitry while still responding passively by backscatter at reverse link.

Class 4 tags **Refers to** active tags with internal power source (battery) and RF transceivers to receive and transmit signals. These tags are more complex than passive tags and have higher read range.

Class 5 tags **Refers to** active tags like the Class 4 tags, however, they have the additional capability of powering up passive tags also.

Classical match filter A simple and powerful signal processing technique for detecting signals in random noise using correlation process.

Cloning An RFID active attack by copying the tag information to an unauthorized blank tag and sending the fake transmission to fool the reader.

Collision Simultaneous presence of data from two or more sources in a communications channel.

CMOS Stands for Complementary Metal Oxide Semiconductor technology that is considered the best choice for low power chip designs due to their insignificant levels of static power dissipation.

Conductivity Electrical conductivity is a materials' ability to conduct electricity.

Conductor Materials that conduct electricity like metals that cause a significant performance decrease in RFID tags due to signal cancelation and detuning tag antenna.

Continuous Wave (CW) Electromagnetic waveform used in narrowband radio transmission where data is represented by a modulating a fixed carrier frequency.

dB In signals and communications systems, Decibel is a logarithmic unit that describes the power ratio of two signals.

dBm Refers to Decibel in miliWatts and is a logarithmic unit of power with respect to 1 mWatt reference signal.

Data Rate Same as data capacity in communication channels is the amount of data transfer in time and is measured as bits/sec.

Denial of service Active attack to RFID systems by using interferers at tag operational frequency to jam the original signals and hinder the service to authorized users.

Demodulation Recovering encoded data from a modulated signal in a communication channel.

De-tuning The presence of conductive materials near the RFID tags causes detuning of the antenna, so the antenna would resonate at a different frequency degrading the tag performance.

Dielectric Materials that are not able to conduct electric current and are used as insulators.

Dielectric constant Represents relative permittivity and is the ratio of permittivity of a material to the permittivity of vacuum. Materials with high dielectric constant reflect more RF energy and cause performance degradation for RFID tags.

Digital cryptography Technique to send digital data securely over communications channels that are not secure. A public or private key will be used to decipher the received data in different cryptography algorithms. Examples of digital cryptography techniques are DES, 3DES, AES.

Dipole antenna One of the basic forms of radio antenna that can be made from a wire or any long conductor with a length equal to half of the wavelength of its carrier signal.

Dispersion The stretch that RF pulses experience during transmission in a wireless communication channel.

Distortion Signal degradation that happens in a wireless channel due to the presence of noise and interferers.

Duty cycle Measure of the fraction of time that an RF pulse is present and is used to calculate the total output power with respect to peak and average power.

EIRP Equivalent isotropic radiated power defines the strength of a signal leaving a directional antenna relative to the performance of an isotropic antenna.

Electric field coupling Refers to tag/reader data transfer at higher frequencies where a passive tag can be powered using the voltage difference between its electrodes while placed in the electric field of its reader.

Electromagnetic Field Refers to a physical field generated by acceleration of charged particles in electrically charged materials and objects.

Electromagnetic spectrum The range of all frequencies for electromagnetic radiation represented in terms of frequency (Hz).

Electromagnetic wave Sinusoidal signals formed by interaction of electrical and magnetic fields with electric and magnetic components perpendicular to each other.

Electronic Product Code A unique identifier developed by MIT Auto-ID center to distinguish the product category and its manufacturers.

EPCglobal An organization to commercialize the electronic product code (EPC) technology.

Encryption Algorithmic scheme to convert data to a form that is not understandable by others who do not have access to the decryption (decipher) key.

Equivalent time sampling A key technique for sampling of signals in UWB radars. In this technique, the UWB waveform is re-constructed from sequential sampling of the return signal, a sample at each pulse repetition interval and with each successive pulse the sampling point range being incremented slightly.

ETSI Stands for European Telecommunications Standards Institute, a European organization that for standardization of wireless technology.

Far Field A region in electromagnetic radiation field that is about 2 wavelengths of the radiated RF signal from its antenna to infinity. In this region the RF power has inverse relations to the square of the distance from antenna.

Faraday's law In electromagnetism theory, Faraday's law refers the voltage induced in the coil with respect to the rate of change in magnetic flux.

FCC stands for Federal Communications Commission, an organization in US that regulates frequency spectrum for various radio, television, and satellite services.

Ferrous material A common term used for conductive materials that contain iron or its derivatives such as steel.

FFT Stands for Fast Fourier Transform and is a computational method to represent spectral components of a signal.

Form factor Terminology for packaging electric circuits that is directly related to their complexity and cost.

Forward Link In RFID terminology, forward link refers to communications from reader to the tag.

Fractional bandwidth Defined as the ratio of the center frequency to total bandwidth of a signal. Fractional bandwidth (B_f) classifies signals as: narrowband with B_f <1%, wideband 1%<20%, ultra-wideband with B_f>20%.

Frequency Measure of spectral component of signals expressed in Hz and is the number of cycles per second in a periodic signal.

GPR Stands for Ground penetrating radar used for detecting underground objects using RF pulses that are transmitted into the ground and reflected by various materials with different dielectric properties. GPR systems are widely used for search and rescue missions as well as various geophysical discoveries.

GPS Stands for Global Positioning System that is a space based navigation system used to locate a receiver on earth from satellites.

Hertzian dipole Defines a category of small dipole antennas that their size is much smaller than 1 wavelength of their transmitted signal.

Heterodyning The process to change a signals center frequency by operations such as mixing or multiplying two or more signals.

High-frequency (HF) In RFID terminology, HF systems operate at 13.56 MHz and are used for applications that require short read ranges (about 1 meter) and medium size data rates (Kbps).

High pass filter A class of electronic circuits in signal processing and RF design that reject the low of frequencies of a signal and only pass high frequencies.

Horn antennas Directional antennas that are used for transmission and reception of RF signals at microwave frequencies.

IF Filtering Stands for intermediate frequency in heterodyning process where the RF signals are first translated to an intermediate frequency stage for ease of filtering before being converted to the desired frequency band.

IFF Identification, Friend or Foe is a technique used by the British forces in World War II where a transponder attached to the fuselage of an aircraft was used to transmit RF signals with a unique signature to communicate with its base as a friendly aircraft returning from a mission.

Impedance matching RF design practice that is required for efficient transfer of power from the source to the load (antenna).

Inductive coupling A method for transferring energy from reader to a passive tag by varying the magnetic flux in both tag and reader antenna coil. Inductive coupling is for short range applications with short read range requirement with HF operating frequency.

Interference Disturbance of RF signals due to intentional or unintentional electromagnetic radiation from other sources, including RF interference from multiple tags to each other in an RFID system.

Interference mitigation Methods and algorithms to suppress unwanted signals from various sources to improve the performance of a wireless communication system such as RFIDs.

Interrogator A reader system that reads RF tag signals. In passive RFIDs, the interrogator powers up the tags and read their modulated data, where in active RFID systems, the interrogator is used to initiate the communications and read the tag data.

ISM Stands for Industrial, Scientific, and Medical radio frequency band that allow unlicensed radiation by various equipments.

LOS Line-of-Sight defines electromagnetic signals that travel n a straight line from transmitting antenna to the receiver antenna.

Low-frequency This frequency band covers the RF spectrum from 125 KHz to 134 KHz and provides good signal penetration through a range of materials including human body or various walls and barriers.

LTCC The Low Temperature Cofired Ceramic technology is a multilayer circuit fabrication technology that has several benefits such as thermal stability, good electrical properties, low cost, and excellent reliability.

Magnetic field coupling Magnetic field coupling is a method for energy transfer from reader to tag where the tag antenna is inductively coupled with the strong electromagnetic (EM) field around the reader's antenna coil.

Memory In the context of RFID systems, memory is an electronic chip that stores the information on a tag. Examples of various types of memory used for RFID tags include: read-only Memory (ROM), Write Once-Read Many Memory (WORM), Erasable, Programmable Read-Only Memory (EPROM).

Microcontroller A single chip with computational capabilities that contains a central processing unit (CPU), various types of memory such as ROM, EPROM, etc., internal clock and control circuitry with input and output ports.

Microstrip antenna A class of antennas usually used for UHF signals that is made out of a conductor plane printed on top of a grounded dielectric substrate.

Microwave tags **RF tags in microwave band** (2.4 GHz), offer high data transfer rates (Kbps) and long distances (~30 m) and is typically used in toll collection applications.

Middleware A specialized software platform that plays a crucial role of bridging RFID readers to the application software.**Mixer:** RF mixers convert signals with a specific frequency to different desired frequencies.

Modulation A technique for encoding data on a RF waveform for transmitting signals from a source to destination.

Monopole antenna A class of RF antennas where conductor is mounted on a ground plane in right angels. Monopole antennas can be considered as half of a dipole antenna.

Multipath A phenomenon in wireless communications that is caused by reflecting signals from multiple surfaces and objects that combine with original signal and result in signal degradation.

Narrowband In RF communications, narrowband signals are the ones that have a fractional bandwidth of less than 1%.

Near-field communication Nearfield communications occurs mostly in LF and HF RFID systems where the distance between the tag and the reader antenna is much smaller than their wavelength.

NLOS Non-line-of-sight signal in RF communication results from multipath phenomenon and is responsible for poor performance of wireless RF communication systems in cluttered environments.

Noise Channel noise in wireless communication systems comes from interfering signals and thermal noise in the wireless medium.

Omnidirectional An antenna that is capable of transmitting and receiving signals in all directions.

On-off Keying (OOK) On-off keying is a type of data modulation that the presence or absence of a carrier signals or a pulse represents digital data.

PAM Stands for Pulse Amplitude Modulation, where changing the height of an RF pulse represents digital data.

Passive Tag RFID tags that have no onboard source of power such as a battery; instead these tags obtain their operational power from harvesting the electromagnetic energy emitted from their reader in close vicinity.

PEC Perfect electric conductor is an ideal material with infinite conductivity that does not produce any losses.

Penetration RF penetration is the ability of signals to propagate through different environments and materials.

Periodic signal RF signals that repeat their characteristics in regular and repeatable intervals.

Permeability The ability of a material to become magnetic in the presence of an applied magnetic field.

Permittivity The measure of a materials resistance to form an electric field.

Phase jitter Deviation of a pulse phase that results in temporary shortening or lengthening of pulses and result in synchronization difficulties.

Physical layer The first layer of open system interconnection (OSI) model that is responsible for transmission and reception of raw data in data communications.

PSD Power spectral density is the distribution of signal power in frequency domain.

Poynting vector The power delivered in the wave radiated from and to an antenna is the vector product of its electric and magnetic fields.

PPM Pulse position modulation is a form of signal modulation where the digital information is encoded based on position of pulses in a sequence.

PRI Pulse repetition interval is the timing between repeating pulses in a sequence.

Radar Stands for Radio detection and ranging is a radio device that is used for locating various targets by transmitting radio signals to the target and detecting its range using time of arrival of the reflecting signals.

RCS Radar cross section of an object is its ability to reflect radar signals and is directly related to the size of the target object.

RF Radio frequency refers to any frequency within the electromagnetic spectrum associated with radio wave propagation.

RFID Radio Frequency IDentification is an enabling technology for remotely identifying, monitoring, and tracking various objects of interest using radio wave transmissions.

Read Range The maximum distance between tag and antenna for reliable data transfer.

Reader A specialized radio whose antenna collects the signals sent tags. In other words, the reader acts as a bridge between the application software and the tags that transmit information.

Read Only In read only tags, data is once written and stored at manufacturing time and can be read by the users multiple times.

Read Rate The amount of data that can be read from a tag per second.

Read/Write Read/write tags are the class of tags that can be written and read by the user.

Rectanna Another term for a rectifying antenna.

Reflection coefficient A parameter in antenna theory that defines the relation between the amplitude of a forward and backward traveling waveforms.

Relay attack A form of adversary attack in RFID systems where one or multiple unauthorized readers can be placed between a tag and its reader to detect and change or counterfeit the transmitted signal between the tag and its legitimate reader

Replay attack An RFID active attacking method where a **cloned** tag sends the same electromagnetic signal to the reader; the fake transmission fools the monitoring system thinking that a high value item is still in its place.

RS232 A physical interface standard that is used in to computer serial ports.

Semi-passive tags Semi-passive or battery assisted passive (BAP) RFID tags include a power source that is only activated when tags are "awakened" by their reader. Therefore, their battery lasts longer than active tags and their read range is longer than passive tags.

Schottky diode A class of diodes have low forward voltage drop across their terminals (approximately 0.15-0.45 V).

Skin depth A representation for penetration depth of electromagnetic signals within a conductor

SNR A representation of the ratio of signal level to the level of noise present in a communication channel and is measured in decibels.

SOC Integrating all components of an electronic circuitry on a single integrated circuit (IC).

Spectrum Mask The maximum power density of a transmitted signal over a certain frequency band.

Spoofing An active attack to RFID systems similar to cloning and replay attacks.

SRD Step recovery diodes semiconductor junction diodes that are used to generate narrow electromagnetic pulses by rapid change of forward bias to reverse bias.

Synchronization Harmonizing the transmission of data from multiple transmitters, or between transmitters and receivers.

Tag An RFID tag or transponder is a small device (generally smaller than the size of a credit card) that is comprised of a small antenna attached to a microchip and an integrated circuit (IC) to store the information unique to the object that it's attached to.

TH-PPM Pulse position modulation with time hopping is a UWB modulation technique where each PPM modulated bit follows a specific time hopping sequence.

Time-reversal technique Signal processing technique that takes advantage of the properties of a signals system response in reverse time.

TR Transmitted Reference technique is a UWB data modulation technique where data is represented by two pulses separated by a unique delay. This method has widely used for synchronization of spread spectrum systems prior to its use in UWB technology.

Transceiver A device that has both transmitter and receiver circuitry.

Transponder Anther name for an RF tag.

Ultra High Frequency (UHF) RF tags operating in UHF band (868 MHz to 928 MHz) use backscatter technology for their tag-reader communications where the tag reflects back the electromagnetic signal it receives from its reader.

UWB Stands for Ultra Wideband, a wireless technology which uses narrow RF pulses to transfer the digital information over a very wide frequency spectrum.

Very High Frequency (VHF) Radio frequency spectrum containing signals with 30 MHz to 300 MHz.

Vivaldi antenna A specialized planar horn wideband antenna that is compact and inexpensive to fabricate.

WBAN Wireless body area network where various wearable sensors can transmit vital signals such as ECG and EEG from human body to a central location.

WLAN Wireless local area network is technology for high-speed wireless data communication in local network environments.

Write Once Read Many (WORM) RF tags that are written once by the user and can be read multiple times.

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