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Ultrawide Bandwidth RFID: The Next Generation?

Ultrawideband technology is seen to be a promising means to provide improved area coverage, better resilience to interference, high multiple-access capability, and ranging resolution to RFID systems.

By Davide Dardari, Senior Member IEEE, Raffaele D’Errico, Member IEEE, Christophe Roblin, Member IEEE, Alain Sibille, Senior Member IEEE, and Moe Z. Win, Fellow IEEE

ABSTRACT | Future advanced radio-frequency identification (RFID) systems are expected to provide both identification and high-definition localization of objects with improved reliability and security while maintaining low power consumption and cost. Ultrawide bandwidth (UWB) technology is a promising solution for next generation RFID systems to overcome most of the limitations of the current narrow bandwidth RFID technology such as: reduced area coverage, insufficient ranging resolution for accurate localization, sensitivity to interference, and scarce multiple-access capability. In this paper, a survey of current progress in the application of the UWB technology for RFID systems is presented with particular attention to low-complexity solutions for high-definition tag localization.

KEYWORDS | Backscatter modulation; localization; radio-frequency identification (RFID); ultrawide bandwidth (UWB)

I. INTRODUCTION

Radio-frequency identification (RFID) technology for use in real-time object identification is facing rapid adoption in several fields such as logistic, automotive, surveillance, automation systems, etc. [1]. An RFID system consists of readers and tags applied to objects. The reader interrogates the tags via a wireless link to obtain the data stored on the tags. The cheapest RFID tags with the largest commercial potential are passive or semipassive, where the energy necessary for tag–reader communication is harvested from the reader’s signal or the surrounding environment. Passive RFID tags are based on backscatter modulation where the antenna reflection properties are changed according to information data [2].

Future advanced RFID systems are expected to provide both reliable identification and high-definition localization of tags. New important requirements will be accurate real-time localization at the submeter level, management of large number of tags, in addition to extremely low power consumption, small size, and low cost [3]. Unfortunately, most of these requirements cannot be fulfilled completely by the current first- and second-generation RFID [4] or wireless sensor network (WSN) technologies such as those based on the ZigBee standard [5]. In fact, RFID systems using standard continuous wave oriented communication in the ultra-high-frequency (UHF) band have an insufficient range resolution to achieve accurate localization, are affected by multipath signal cancellation (due to the extreme narrow bandwidth signal), are very sensitive to narrowband interference and multiuser interference, and have an intrinsic low security [1], [6]–[8]. Although some of these limitations, such as security and signal cancellation due to multipath, are going to be reduced or overcome in future versions of UHF RFID systems [9]–[11], a technology change is required to fully satisfy new applications requirements, especially those related to high-definition localization at the submeter level.
A promising wireless technique for next generation RFID is the ultrawide bandwidth (UWB) technology characterized, in its impulse radio UWB (IR-UWB) implementation, by the transmission of subnanosecond duration pulses. The employment of wideband signals enables the resolution of multipath, the mitigation of frequency-dependent fading, and high localization precision based on time-of-arrival (TOA) estimation of the signal. The potential advantages of UWB include, but are not limited to, low power consumption at the transmitter side, extremely accurate ranging and positioning capability at the submeter level, robustness to multipath (better area coverage), low detection probability (higher security), large numbers of devices operating, and coexisting in small areas (efficient multiple channel access and interference mitigation) [7], [12]–[15].

Thanks to their low power consumption, IR-UWB transmitters have successfully been adopted for active tags [16]–[18], even though passive solutions based on backscatter signaling appear to be preferable when low-cost and small-size requirements become crucial. However, UWB RFID solutions based on backscatter modulation are in their embryonic stage and several issues still have to be investigated as will be highlighted in the next sections [19].

This paper presents a survey of the UWB technology and its current application for RFID systems to illustrate the potential of this technology for next generation RFID systems. Particular emphasis will be paid to solutions based on passive UWB RFID tags due to their low cost and hence wider market perspectives. This paper is organized as follows. Section II provides an overview of UWB technology and Section III describes the main characteristics of UWB propagation and antennas. The most interesting solutions proposed for active and passive tag architectures are analyzed, respectively, in Sections IV and V by highlighting their potential capabilities in providing high-definition localization performance. Finally, some conclusions are given in Section VI.

II. THE UWB TECHNOLOGY

A. UWB—Definitions and Regulatory Issues

The most widely accepted definition of a UWB signal is a signal with instantaneous spectral occupancy in excess of 500 MHz or a fractional bandwidth of more than 20% [20]. Such signals are usually generated by driving an antenna with very short electrical pulses (duration on the order of one nanosecond or less). As opposed to narrowband systems, antennas in UWB systems, due to the very large signal bandwidth, determine a significant pulsedoing filtering.

In 2002, the U.S. Federal Communications Commission (FCC) issued the First Report and Order, which permitted unlicensed UWB operation and commercial deployment of UWB devices. The FCC allocated a block of unlicensed radio spectrum from 3.1 to 10.6 GHz at the maximal power spectral density of $-41.3 \, \text{dBm/MHz}$, where each class of devices was allocated a specific spectral mask and UWB radios overlaying coexistent radio-frequency systems can operate as described in [20]. Regarding Europe, it is important to mention that on February 21, 2007, the Commission of the European Communities released a decision on allowing the use of the radio spectrum for equipments using UWB technology in a harmonized manner in the European Union community [21].

B. Impulse Radio UWB

The IR-UWB technique relies on ultrashort (nanosecond scale) pulses that can be free of sine-wave carriers and do not require intermediate frequency processing because they operate at baseband, thus significantly reducing the hardware complexity and power consumption. The IR-UWB technique has been selected as the physical layer of the IEEE 802.15.4a Task Group for wireless personal area networks (WPAN) [22] and it is promising for RFID applications.

In IR-UWB, the information is encoded using impulses. Typically, the adopted pulse $p(t)$ is derived from the Gaussian pulse $p_0(t) = \exp(-2\pi (t^2/\tau_p^2))$ and its derivatives due to its smallest possible time-bandwidth product which maximizes range-rate resolution and is readily available from antenna pattern. In general, due to the short pulse duration (typically less than 1 ns), the bandwidth of the transmitted signal is on the order of one or more gigahertz. These pulses can be modulated using either pulse position modulation (PPM) or pulse amplitude modulation (PAM). An impulse-based radio allows for a simple circuit structure with low power dissipation since there is no need to up-convert a carrier signal [23]. The transmitter feeds these impulses to a very large bandwidth nonresonating antenna, or sometimes the antenna itself contributes to proper spectral shaping.

In a typical IR-UWB communication system, a symbol of duration $T_s$ is divided in time intervals $T_f$ called frames, which are further decomposed into smaller time slots $T_c$ called chips. To allow for multiuser access, the pulse $p(t)$, with duration $T_p < T_c$, is transmitted in each frame in a chip position specified by a user-specific pseudorandom time-hopping code $\{c_k\}$ having period $N_s$, where $N_s$ is the number of frames per symbol [12]. The frame time $T_f$ is usually chosen to be greater than the maximum multipath delay to avoid intersymbol interference. The information can be associated with pulse polarity leading to PAM signaling or with pulse position thus obtaining a PPM signaling scheme.

The simplest UWB receiver is a correlation receiver [12] where the received signal is correlated with a local replica (template) of the transmitted pulse $p(t)$ or, equivalently, is passed through a filter matched to $p(t)$ [matched filter (MF)].
Typical indoor environments often exhibit the presence of a dense multipath with delay spread much larger than the resolution capability of the signal being employed [24]. The transmission of ultrashort pulses can potentially resolve extremely large number of paths experienced by the received signal thus eliminating significant multipath fading. This may considerably reduce fading margins in link budgets and may allow low power transmission operation. In addition, rich multipath diversity can be collected through the adoption of Rake receivers which combine the signals coming over resolvable propagation paths in a way that maximizes the signal-to-noise ratio (SNR) [25].

C. Ranging Capability of UWB Signals

Distance estimation (ranging) between tags and multiple readers represents the first step to localize the tag using, for example, multilateration algorithms [26], [27]. Considering that the electromagnetic (e.m.) waves travel at the speed of light \( c = \frac{3 \cdot 10^8}{1} \) m/s, the distance estimate can be obtained from the measurement of the time-of-flight \( \tau \) of the signal and by observing that \( \tau = d/c \), where \( d \) is the actual distance between the tag and the reader. This requires an accurate estimation of the TOA of the received signal.

To understand which fundamental system parameters dominate ranging accuracy, an overview of the performance limits of TOA estimation is presented in additive white Gaussian noise (AWGN) channels. Consider a scenario in which a unitary energy pulse \( p(t) \) is transmitted (with duration \( T_p \)) through an AWGN channel. In the absence of other error sources, the received signal can be written as

\[
r(t) = \sqrt{E_p} p(t - \tau) + n(t)
\]

where \( E_p \) is the received energy and \( n(t) \) is AWGN with zero mean and two-sided power spectral density \( N_0/2 \). The goal is to estimate the TOA \( \tau \), and hence the distance \( d \), by observing the received signal \( r(t) \). This task can be challenging due to the presence of thermal noise and multipath components. Under this simple model, TOA estimation is a classical nonlinear parameter estimation problem, with a solution based on an MF receiver [13]. As shown in Fig. 1, the received signal is first processed by a filter matched to the pulse \( p(t) \) [or, equivalently, by a correlator with template \( p(t) \)]. The TOA estimate is given by the instant corresponding to the maximum absolute peak at the output of the MF over the observation interval. This scheme yields a maximum-likelihood estimate, which is known to be asymptotically efficient, that is, the performance of the estimator achieves the Cramér–Rao bound for large SNRs.\(^1\)

The mean square error of any unbiased estimate \( \hat{d} \) of \( d \), derived from TOA estimation, satisfies the following inequality [13]:

\[
\text{Var}(\hat{d}) = \mathbb{E}\{\varepsilon^2\} \geq \frac{\varepsilon^2}{8\pi^2 B^2_{\text{eff}} \text{SNR}}
\]

where \( \varepsilon = \hat{d} - d \) is the ranging estimation error. The right-hand side term in (2) represents the Cramér–Rao bound. Here SNR \( = E_p/N_0 \) and parameter \( B^2_{\text{eff}} \) represent the second moment of the Fourier transform \( P(f) \) of \( p(t) \),\(^2\) that is

\[
B^2_{\text{eff}} = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |f|^2 |P(f)|^2 df}{\int_{-\infty}^{\infty} |P(f)|^4 df}.
\]

Notice that the lower bound in (2) decreases with both SNR and the constant \( B^2_{\text{eff}} \), which depends on the shape of the pulse. This demonstrates that signals with high power and wide transmission bandwidth are beneficial for ranging.

\(^1\)The Cramér–Rao bound gives the theoretical limit on the mean square error of any unbiased estimator, and hence, it represents a useful benchmark to assess the performance of any practical estimator.

\(^2\)Parameter \( B_{\text{eff}} \) is often called the effective bandwidth.
Fig. 2 shows the root mean square error (RMSE) for Cramér–Rao bound using the second- and sixth-order Gaussian monocycle pulses with, respectively, $\tau_p = 1$ ns and $\tau_p = 0.192$ ns, and $\tau_p = 0.192$ ns are considered [13].

Fig. 2 shows the root mean square error (RMSE) for Cramér–Rao bound using the second- and sixth-order Gaussian monocycle pulses with $\tau_p = 1$ ns and $\tau_p = 0.192$ ns, respectively. Note that higher derivative Gaussian monocycles or lower $\tau_p$ correspond to a lower bound. Fig. 2 also shows the RMSE for the improved Ziv–Zakai bound which is tighter than the Cramér–Rao bound for medium and low SNRs [13]. Centimeter level accuracy is potentially feasible using UWB signals.

In more realistic environments, numerous practical factors might affect ranging accuracy. Sources of error from wireless signal propagation include multipath, direct path excess delay, and blockage incurred by propagation of a partially obstructed or completely obstructed direct path component that travels through obstacles such as walls in buildings [13].

### III. UWB BACKSCATTER PROPAGATION

As previously mentioned, passive RFID tags are based on backscatter modulation where the antenna reflection properties are changed according to information data [2]. In general, when an e.m. wave encounters an antenna, it is partially reflected back depending on antenna configuration. The antenna scattering mechanism is composed of structural and antenna mode scattering [28]. The structural mode occurs owing to the antenna’s given shape and material and is independent from how the antenna is loaded. On the other hand, antenna mode scattering is a function of the antenna load, thus data can be sent back to the reader through a proper variation of the antenna load characteristic without requiring a dedicated power source (backscatter modulation). This property is currently adopted in traditional passive UHF RFID tags based on continuous wave signals to carry information from the tag to the reader.

As compared to the extensive investigations of UHF RFID (see [2], [6], [28], and [29]), further investigation of backscatter properties when operating with UWB signals, especially in realistic environments, is needed [30]–[32].

When a UWB pulse is transmitted and UWB antennas are employed, the reflected signal takes the form shown in Fig. 3. The structural and antenna mode scattering components are plotted separately for convenience. The far field radiated from the reader and incident to the tag is partially backscattered according to the antenna scattering characteristics which depend on the antenna load (different load configurations will be referred to as tag status X) and reader–tag orientation in the 3-D space $\Theta = \{\Theta_r, \Theta_t\}$, with $\Theta_r = (\theta_{\text{tag}}, \phi_{\text{tag}})$ and $\Theta_t = (\theta_{\text{reader}}, \phi_{\text{reader}})$ being the tag and reader orientation, respectively.

The antenna mode scattered signal can be varied according to the antenna load $Z_L$, whereas the scattering of the structural mode remains the same. Among the various possibilities, three particular choices are of interest for passive UWB RFID: $Z_L = 0$ (short circuit), $Z_L = \infty$ (open circuit), and $Z_L = Z_A^*$ (matched load), where $Z_A$ is the conjugate antenna impedance. Ideally, antenna mode scattered waveforms have a phase difference of 180° between the case of open and short circuit loads, whereas no antenna mode scattering exists in the case of a perfect matched load. In UWB antennas, the structural mode component takes a significant role in the total scattered signal; in fact, it is typically one or two orders of magnitude higher than that of the antenna mode [30]–[32]. In addition, signals scattered by the surrounding environment (clutter) are inevitably present and superimposed on the useful signal. In general, it is expected that the clutter and the antenna structural mode scattering dominate the signal received by the reader, thus making the detection of the antenna mode scattered signal (which carries data) a main issue in passive UWB RFID systems. This has not yet

![Fig. 3. Example of backscatter mechanism for the transmitted pulse due to the tag’s antenna and the presence of scatterers.](image-url)
been addressed, and to this purpose, the design of ad hoc robust backscatter modulation schemes is a fundamental issue as will be illustrated in Section V.

In Fig. 4, the backscattered signal is shown from a balanced antipodal Vivaldi antenna, realized on strip-line technology, for open and short load conditions in the direction of maximum radiation using a balanced antipodal Vivaldi antenna. A delay line of 1.375 ns was inserted between the reference antenna port and the load for an easy temporal discrimination of the antenna mode [19].

Fig. 4. Measured backscattered signal at reference distance \( d_{\text{ref}} = 1.44 \text{ m} \) for different load conditions in the direction of maximum radiation using a balanced antipodal Vivaldi antenna. A delay line of 1.375 ns was inserted between the reference antenna port and the load for an easy temporal discrimination of the antenna mode [19].

the other hand, a UWB receiver, even simple, is typically characterized by higher values of consumed power (as much as 100 mW) [35]. Therefore, devices based on the IEEE802.15.4a standard for WSNs (which allows for bidirectional communication) do not fit RFID application requirements. For this reason, most of proposed UWB RFID devices, typically designed for real-time locating systems (RTLSs), only have transmitting tags operating with low duty cycle in order to extend battery operation up to a few years [16]–[18].

An alternative solution is proposed in [33] where the concept of a pseudorandom active reflector is introduced. As shown in Fig. 5, the reflector consists of a simple device that repeats a slightly delayed version of the received UWB signal in certain specific time intervals according to a suitable pseudorandom time-hopping sequence. In particular, the signal received by the antenna is amplified with gain \( G \) and delayed by a fixed quantity \( T_d \) of a few nanoseconds. The delayed version of the signal is used to drive the transmitter section composed of a power amplifier and a UWB antenna. The trigger pulse at the output of the pseudorandom generator enables the receiver amplifier for a certain time window \( T_w \) (activity window). A version delayed by the quantity \( T_d \) of the same trigger pulse is used to enable the transmitter. The transmission and receiving windows are not time overlapped so that no transmitter–receiver coupling occurs and the same antenna can be used for both the transmitter and the receiver. The reader emits pulse trains with the same pseudorandom time-hopping sequence used by the reflector it wants to communicate with. Each reflector has a unique pseudorandom sequence and reflects, with a delay \( T_d \), the received UWB signal for a short time interval according to the time-hopping sequence (see Fig. 5). When synchronized, all transmitted pulses are reflected only by the tag adopting the same pseudorandom sequence of the reader thus making the reader able to collect coherently the energy from that particular tag. As stated in [33], the advantages of this solution are in the simplicity of the hardware where only the analog section is required, in the low power consumption of the tag, and in the low timing constraint regarding the relative transmitter and reflector clock rates.

B. Localization Capability

The first application of UWB technology in the RFID field was for precision asset location systems operating in indoor environments [16]–[18]. In these systems only transmitting tags are employed. Tag position estimation cannot rely on an absolute distance estimate between tag and readers, and localization schemes based on time difference of arrival (TDOA) are usually adopted. In TDOA-based localization systems, UWB burst signals are broadcast periodically by the tag and are received by several readers placed in known positions. The readers share their estimated TOA and compute the TDOA provided that they have a common reference clock. Considering that time

IV. UWB RFID AND LOCALIZATION WITH ACTIVE TAGS

A. Low Duty Cycle UWB Tags

As previously mentioned, an IR-UWB transmitter can be very simple and is characterized by an extremely low duty cycle transmitted signal. Therefore, such a transmitter has low complexity and low consumption (less than 10 mW depending on the pulse repetition rate) [34]. On
measurements are on the order of 1 ns or less, readers must be kept tightly synchronized through a wired network connection. To calculate the position of the tag, at least three readers with known position and two TDOA measurements are required. Each TDOA measurement is geometrically interpreted as a hyperbola formed by a set of points with constant range differences (time differences) from two readers.

Time Domain Plus RTLS is an example of a commercial proprietary system designed for locating personnel or mobile assets adopting TDOA techniques [17]. The active tag is a compact IR-UWB battery-powered transmitter that is designed for long battery duration, up to 4 years (at 2-Hz update rate) or up to 1.5 years (at 4-Hz update rate). The system can locate and track thousands of tags with sub-meter location accuracy using an adequate number of tightly synchronized readers which perform the function of receiving tag packets, demodulating the tag data, measuring the TOA for each tag, and computing the TDOA for location estimation.

Another possibility to localize the tag is to measure the angle of arrival (AOA) of the signal thus obtaining the information about tag direction from neighboring readers. The AOA on an incoming radio signal can be estimated by using multiple antennas with known separation (antenna array) and by measuring the TOA of the signal at each antenna. Given the differences in arrival times and the array geometry, it is possible to estimate the direction of propagation of a radio-frequency wave incident on the antenna array. AOA does not require the precise time synchronization needed for TOA and TDOA techniques. Two angle measurements are required to determine node position (triangulation). In non-line-of-sight environments, the measured AOA might not correspond to the direct path component of the received signal and large angle estimation errors can occur. Due to the presence of multiple antenna elements, AOA techniques are in general more expensive in terms of cost and device dimensions than TOA-based techniques.

The Ubisense platform is an example of a commercial precision localization system where active tags are localized using TDOA or AOA techniques [18]. When AOA localization is performed, tight synchronization among readers is not required thus drastically reducing network requirements, but the positioning accuracy is not good as that obtainable using TDOA measurements.
V. UWB RFID AND LOCALIZATION WITH PASSIVE TAGS

When tag cost, size, and power consumption requirements become particularly stringent, passive or semipassive tag solutions have to be taken into consideration. As already mentioned, communication with passive tags usually relies on backscatter modulation even though the tag’s control logic and memory circuits still have to be energized in order to have the tag working properly. Typically, passive RFID tags obtain the necessary power to operate from the radio-frequency signal sent by the reader. As a consequence, in conventional UHF RFID systems, the corresponding operating range is restricted to be no more than 7–8 m with a transmission power level of 2–4 W [2]. Unfortunately, due to regulatory constraints, the transmission power allowed for UWB devices is below 0 dBm [21]. This means that sufficient power cannot be derived from the received UWB signal to power up a remote tag at significant distance. Besides the adoption of semipassive tags, where the control logic is battery powered, a promising possibility for retrieving the necessary energy is to adopt energy scavenging techniques which, in many cases, provide sufficient power (about 1–10 μW) for the control logic [36]. Another solution is represented by hybrid tag architectures, as illustrated in the following.

A. Hybrid Tags Based on UHF and UWB Modulations

Hybrid tag solutions are proposed in [23] and [37]–[39]. The main idea is to have an asymmetric link where a conventional transmission protocol at UHF in the downlink (reader–tag) is adopted to power up the tag. The accumulate energy allows an IR-UWB transmitter to send data for a short time interval at high data rate in the uplink (tag–reader). Similarly to conventional passive tags, the incoming radio-frequency signal transmitted by the reader at UHF is used to provide power supply and receive the data. In particular, in [23], the reader radiates the radio-frequency signal with no data for at least 7 ms, which is sufficient time for a storage capacitor to fully charge. After enough energy has been collected, the tag switches to the receiving mode to receive commands from the reader at a low data rate (40 kb/s). The uplink transmission is performed using the IR-UWB transmitter. Thanks to the high transmission data rate (1 Mb/s with \( N = 10 \) pulses per bit) and the low transmitter consumption (64 μW), the energy stored in the capacitor is sufficient to allow the transmission of packets containing more than 128 bits. Circuit implementation and simulations have shown that an operating range up to 10.7 m with 4-W effective radiated isotropic power (EIRP) emission is feasible from the energy budget point of view.

Remote powering of a passive UWB tag by UHF has recently been achieved for high data rate exchanges (> 50 Mb/s at a few tens of centimeters) from a cell phone to a tag embedding a large memory [39].

B. Tags Based on Backscatter Modulation

Recently, some applications of the UWB technology in tags based on backscatter modulation have been proposed [19], [40]–[42]. Due to its extremely low complexity, backscatter communication appears very promising, especially in the perspective of the adoption of efficient energy scavenging techniques for the tag’s control logic power supply [36]. For this reason, in the following, more details to this solution are offered.

In Fig. 6, the architectures proposed in [40] and [41] and analyzed in [19], [32], and [43] for tag and reader are shown. The reader is composed of a transmitter and a receiver section both connected to the same UWB antenna through a TX/RX switch. During the interrogation phase, the reader transmits a sequence of UWB pulses, each having energy \( E_t \), modulated by a periodic binary sequence \( \{ d_n \} \) of period \( N_s \), with \( d_n \in \{-1, +1\} \), specific to that particular reader (reader’s code). Without loss of generality, an infinite sequence of pulses separated by \( T_f \) seconds (frame time) is considered, that is

\[
s(t) = \sum_{n=-\infty}^{\infty} d_n \cdot p(t - nT_f)
\]

characterized by a transmission power \( P_t \). The frame time \( T_f \) is chosen so that all signals backscattered by the environment are received by the reader before the transmission of the successive pulse. In an indoor scenario, \( T_f = 50–100 \) ns is usually sufficient for this purpose.

During the transmission of each pulse the antenna is connected to the transmitter section. It is then kept connected to the receiver section during the remaining time until the successive pulse is transmitted. Each pulse in (4) is backscattered by the tag’s antenna as well as by all the surrounding scatterers present in the environment which form the clutter component. The main task of the receiver section of the reader is to detect the useful backscattered signal (i.e., that coming from the tag’s antenna mode scattering which depends on antenna load changes) from those backscattered by the antenna structural mode and other scatterers (clutter) which are, in general, dominant.

For this purpose, in [40] and [41], a quite general backscatter modulator architecture is proposed allowing for different signaling schemes such as PAM, PPM, and on–off keying. Here, for the sake of illustration, the performance of a simplified version of the tag architecture is illustrated by considering the 2-PAM signaling. In this case, the backscatter modulator reduces to a simple switch as shown in Fig. 6. To make the uplink communication robust to the presence of clutter, interference, and to allow...
multiple access, the tag is designed to change its status (short or open circuit) at each frame time \(T_f\) according to the data to be transmitted and a zero mean periodic tag's code \(\{c_n\}\), with \(c_n \in \{-1, +1\}\), of period \(N_s\). Specifically, each tag information symbol \(b_k \in \{-1, +1\}\) is associated to \(N_s\) pulses, thus the symbol time results \(T_s = T_f/N_s\). Therefore, the tag status \(x_n\) at the \(n\)th frame time is \(x_n = (c_n b_{[n/N_s]} + 1)/2\) and can take the values \(x_n = 0\) (open circuit) and \(x_n = 1\) (short circuit).\(^3\) In this way, the polarity of the reflected signal changes according to the tag's code during a symbol time, whereas the information symbol affects the entire sequence pulse's polarity at each symbol time (see the example of Fig. 7).

In the following analysis, the tag response due to the antenna mode (depending on the data) is considered whereas the antenna structural mode will be treated as a part of clutter since it does not depend on data symbols. In a multipath scenario, the received signal at the reader is

\[
r(t) = \sum_{n=-\infty}^{\infty} \sum_{i=1}^{L} \alpha_i d_{\ell i} w(t - nT_f - \tau_i; x_n, \Theta) + \sum_{n=-\infty}^{\infty} d_{\ell 0} w^{(c)}(t - nT_f) + n(t) \tag{5}\]

where \(n(t)\) is the AWGN with two-sided power spectra density \(N_0/2\), and \(L\) is the number of received paths due to the multipath related to the tag’s antenna mode component of the backscattered signal. Parameters \(\alpha_i\) and \(\tau_i\) are, respectively, the path’s amplitude and delay of the \(i\)th multipath component related to the reader–tag–reader round-trip channel. Assume that \(\tau_i < T_f, \forall i = 1, 2, \ldots, L\) (no intersymbol interference present) and static channel conditions during a symbol time \(T_s\). The function \(w(t; x_n, \Theta)\) represents the backscattered pulse from the \(i\)th path which is in general distorted and depends on the tag status \(x_n\) and on the orientation \(\Theta\). The first path corresponds to the direct path (when it exists) between the reader and the tag and its TOA \(\tau_1\) can be exploited to estimate their reciprocal distance as explained in Section II-C. The signal \(w^{(c)}(t)\) represents the backscattered version of the pulse \(p(t)\) due to the clutter component which also accounts for pulse distortion, multipath propagation, and tag antenna structural mode.

Considering the receiver scheme reported in Fig. 6, where a simple single-path MF demodulator is adopted, the received signal is first passed through a filter having impulse response \(h_{MF}(t)\) to obtain the signal \(v(t) = r(t) \otimes h_{MF}(t)\), where \(\otimes\) is the convolution operator. In the absence of other information, \(h_{MF}(t)\) can be chosen to be proportional to \(w_{ref}(-t; 0, \Theta_{max}) - w_{ref}(-t; 1, \Theta_{max})\), where \(w_{ref}(t; \Theta_{max})\), for \(x = 1\) and \(x = 0\), is the received pulse at the reference distance \(d_{ref}\) in free-space propagation at the orientation \(\Theta_{max}\) of maximum tag’s antenna radiation for open and short load conditions, respectively. This receiver is optimal in AWGN when \(\Theta = \Theta_{max}\), but it is suboptimal in a

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\(^3\)Operator \([x]\) denotes the smallest integer larger than or equal to \(x\).
multipath scenario. In such a case, the receiver in Fig. 6 can be extended easily to a Rake structure composed of a number \( L_p \) of fingers, each of them synchronized to a different path [43].

Supposing perfect code and pulse synchronization to the first arriving path TOA \( \tau_1 \), \( v(t) \) is sampled at sampling intervals \( t_{im} = i T_f + m N_s T_f + \tau_0 \), with \( i = 0, 1, \ldots, N_s - 1 \), thus obtaining the samples \( v_{im} \).\(^4\) Looking at the example in Fig. 7, note that only the antenna mode scattered signals are modulated by the combination of the tag’s and reader’s codes \( \{ c_n \} \) and \( \{ d_n \} \), whereas all clutter signal components (including the antenna structural mode scattering) are modulated only by the reader’s code \( \{ d_n \} \). Then, as shown in Fig. 6, to remove the clutter component at the receiver, the sampled signal \( v_{im} \) is multiplied by the composite sequence \( \{ c_n \cdot d_n \} \), which identifies both the reader and the desired tag.\(^5\)

Considering resolvable multipath, an exponential path-loss model with exponent \( \beta \) [24], and perfect pulse symmetry, i.e., \( w_l(t; 0, \Theta) = -w_l(t; 1, \Theta) \), the bit error probability conditioned to the first path amplitude \( \alpha_1 \) [19] is therefore

\[
P_b = \frac{1}{2} \text{erfc} \left( \frac{P_t G_{\text{ref}} \alpha_1^2 P_t^2 \left( \frac{d_{\text{ref}}}{d} \right)^{2\beta}}{N_0 R_b} \right)
\]

where \( R_b = 1/(N_s T_f) \) is the data rate (symbol rate), \( G_{\text{ref}} \) is the round-trip channel power gain at the reference distance \( d_{\text{ref}} \) and the maximum direction of radiation \( \Theta_{\text{max}} \) in AWGN scenario, and \( \text{erfc}(\cdot) \) is the complementary error function. Parameter \( \rho_l \) represents the normalized cross correlation between pulses \( [w_l(t; 0, \Theta) - w_l(t; 1, \Theta)] \) and \( [w_{\text{ref}}(t; 0, \Theta_{\text{max}}) - w_{\text{ref}}(t; 1, \Theta_{\text{max}})] \), which accounts for the mismatch due to pulse distortion. Note that \( 2\beta \) is present instead of \( \beta \) in (7) to account for the two-way link.

Results on the potential operating range of the passive UWB RFID system are obtained starting from measured data described in Section III using a balanced antipodal Vivaldi antenna and the sixth derivative Gaussian pulse. For the balanced antipodal Vivaldi antenna under test, \( G_{\text{ref}} = -75 \) dB. The following system parameters are considered: \( F = 4 \) dB (reader noise figure), \( G_{\text{reader}} = 5 \) dB (reader antenna gain), \( T_f = 100 \) ns (frame time), \( \beta = 2 \), and \( P_t = -10.2 \) dBm (transmitted power). The transmission power \( P_t \) has been chosen to obtain a transmitted signal compliant with the 3.1–10.6-GHz FCC mask.

\(^4\)Note that the reader and the tags have their own clock sources and hence have to be treated as asynchronous. Only the tag’s code \( \{ c_n \} \), which is not in general time aligned to the reader’s code \( \{ d_n \} \), has to be acquired. For this purpose, powerful acquisition techniques [44] and the TOA estimator proposed in [45] can be adopted. Once the TOA \( \tau_1 \) is estimated, the reader can adjust its internal clock so that it becomes synchronous to that of the intended tag, and the optimal choice for \( \tau_0 \) is obtained. A more general analysis considering asynchronous multiple tags can be found in [43].

\(^5\)Multiple readers can access the same tag by using different reader codes provided they are designed with good cross-correlation properties.

---

**Fig. 7.** Example of reader transmitted and received signals. For simplicity, an all-ones sequence for \( \{ d_n \} \) is considered.
Fig. 8 shows the achievable operating range as a function of the data rate $R_b$ for a fixed target bit error probability $P_b = 10^{-3}$. The operating range related to a single-path MF receiver in AWGN channel ($\alpha_1 = 1$) is considered using measurement data for different tag’s antenna orientation offsets $\phi$ with respect to the maximum radiating angle. It can be seen, for example, that for data rate $R_b = 10^3$ b/s, an operating range larger than 20 m can be achieved, which is significantly larger than the operating range of UHF-based RFID systems (typically 3–4 m), with a dramatically transmitted power level reduction ($\approx 0.09$ mW versus 2–4 W). However, antenna radiation pattern and pulse distortion determine a significant performance degradation when devices are not oriented to the maximum radiating direction as noted in Fig. 8 (see curves with $\phi \neq 0$). This degradation can be mitigated using, for example, multiple readers or antennas [46]. In the same figure, the operating range is evaluated in the presence of multipath with Nagagami-$m$ fading characterized by fading severity parameter $m = 2$ and uniform power delay profile. No pulse distortion is considered, i.e., $\rho_t = \rho_r$ Vl. Larger operating ranges can potentially be obtained when the multipath resolution of UWB signal is exploited by using partial Rake receivers (see, for example, the curves corresponding to $L_p = 8$ fingers). A more extensive analysis and other results obtained in a typical indoor environment can be found in [32] and [43]. It is important to remark that ongoing work in the European Regulatory Framework is trying to establish that location tracking equipment, operating indoors in the reduced frequency band 6.4–8.5 GHz, could increase both the average and peak EIRP by up to 10 dB ($-31.3$ dBm/MHz and 10 dBm/50 MHz, respectively), provided their duty cycle does not exceed 2.5% [21]. This would mean ten times increased data rate, thus making passive UWB RFID very attractive for next generation RFID systems. However, for a complete characterization of passive UWB RFID technology, important related topics that have not yet been sufficiently addressed in the literature need to be investigated, for example, experimental clutter and round-trip multipath channel characterization, performance assessment in the presence of multiple tags/readers, and narrowband interference [43].

C. Localization Capability

The theoretical performance of a localization system is investigated based on passive UWB tags. Consider a scenario composed of $N$ readers placed at known coordinates which interrogate a tag located in unknown coordinates with the purpose of obtaining an estimate of the reader–tag distance (through the measurement of the round-trip time of the backscattered signal) and determine the tag’s position by means, for example, of a classical multilateration localization algorithm [26], [27].

In Fig. 9, an example is given of theoretical achievable localization accuracy in a square area of $20 \times 20$ m$^2$ composed of $N = 4$ readers. Results are derived starting from measured data in AWGN and considering random tag orientation. The same system parameters used in Section V-B are considered with $N_s = 1000$. In particular, Fig. 9 shows the covered locations in a predefined grid, where a location is defined as covered if for at least 70% of possible tag orientations the localization estimation does not exceed 2.5% [21]. This would mean ten times increased data rate, thus making passive UWB RFID very attractive for next generation RFID systems. However, for a complete characterization of passive UWB RFID technology, important related topics that have not yet been sufficiently addressed in the literature need to be investigated, for example, experimental clutter and round-trip multipath channel characterization, performance assessment in the presence of multiple tags/readers, and narrowband interference [43].

Fig. 8. Tag–reader operating range in meters as a function of the data rate for $P_b = 10^{-3}$ and different tag orientations, channel and receiver configurations [19].

Fig. 9. Coverage map using four readers (R1–R4) and passive UWB tags. Locations with position estimation RMSE less than 20 cm are marked.
While active UWB RFID commercial systems have recently appeared, the study of semipassive or passive UWB RFID solutions, which are particular attractive for low-cost applications, is at the beginning. Important related topics need to be investigated such as the experimental characterization of clutter and round-trip multipath channel in realistic environments as well as the design of small-size UWB antennas. In the near future, the availability of ad hoc standards will also become a relevant issue.

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RMSE is less than 20 cm. Note that even in a relatively large area, the number of locations covered with high accuracy results is quite large, thus making submeter accuracy localization using backscatter signaling feasible.
ABOUT THE AUTHORS

Davide Dardari (Senior Member, IEEE) received the Laurea degree in electronic engineering (summa cum laude) and the Ph.D. degree in electronic engineering and computer science from the University of Bologna, Bologna, Italy, in 1993 and 1998, respectively.

He is an Associate Professor at the University of Bologna at Cesena, Cesena (FC), Italy. He is Research Affiliate with WLAB and Wireless Communications Group, LIDS, Massachusetts Institute of Technology (MIT), Cambridge. His actual research interests are in ultrawide bandwidth communication and localization, wireless sensor networks, and OFDM systems. He published more than 100 technical papers and played several important roles in various national and European projects. He is coauthor of the book Wireless Sensor and Actuator Networks: Enabling Technologies, Information Processing and Protocol Design (New York: Elsevier, 2008).

Dr. Dardari is the current Co-Chair of the Radio Communications Committee of the IEEE Communication Society. He is Co-General Chair of the 2011 IEEE International Conference on UWB (ICUWB). He was Co-Chair of the Wireless Communications Symposium of the 2007 IEEE International Conference on Communications (ICC) and of the 2006 IEEE ICUWB. He was Lead Editor for the EURASIP Journal on Advances in Signal Processing (Special Issue on Cooperative Localization in Wireless Ad Hoc and Sensor Networks), Guest Editor for PROCEEDINGS OF THE IEEE (Special Issue on Cooperative Localization in Wireless Ad Hoc and Sensor Networks), and Associate Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS.

Raffaele D’Errico (Member, IEEE) received the Laurea degree in telecommunication engineering from the University of Bologna, Bologna, Italy, in 2005 and the Ph.D. degree in telecommunication engineering from University of Orsay, Paris XI, France and University of Bologna, in 2008.

Since 2008, he has been with the Laboratory of Electronics and Information Technology, French Atomic Energy Commission (CEA-LETI), Grenoble, France, working on channel modeling and small antenna design. His research activity is concerned with UWB single- and multiple-antennas design and channel modeling for body area networks and wireless sensor networks.

Dr. D’Errico received the Best Paper Award in at the 2009 IEEE Personal, Indoor and Mobile Radio Communications Symposium (PIMRC).

Christophe Roblin (Member, IEEE) received the degree in electrical engineering from the Ecole Nationale Supérieure de l’Aéronautique et de l’Espace, Toulouse, France, in 1987 and received the Ph.D. degree in submillimeter receivers for radio astronomy in 1992.

Currently, he is Head of the Adaptive Antennas and High Data Rate Radiocommunications Group and Associate Professor at ENSTA-ParisTech (Ecole Nationale Supérieure de Techniques Avancées ParisTech), Paris, France. He has a strong experience in microwave circuit and antenna design and modeling. Since 2002, his research activities have been in the area of ultrawideband communications, focussing on UWB antenna design, characterization and parametric modeling. He is also currently involved in antenna and channel topics for body area networks. He has significantly contributed to several European projects—ADAMO (FP4), ULTRAWAVES (FPS), and PULSERS I & II—and has been the ENSTA team leader for PULSERS I and the French National Research Agency (ANR) project BANET. He has authored or coauthored more than 70 publications and communications.

Alain Sibillé (Senior Member, IEEE) received the degree from Ecole Polytechnique, Palaisseau Cedex, France, in 1977, the degree from Telecom-ParisTech, Paris, France, in 1979, and the Ph.D./habilitation degree from University of Paris 7, Paris, France, in 1985.

He first conducted basic research within France-Telecom R&D and later as a part-time independent consultant. Then, he moved to ENSTA-ParisTech, Paris, France, where he now leads the Electronics and Computer Engineering Department. His current scientific interests lie in ultrawideband communications and systems, and in the interactions between antennas, channels, and signal processing.

Prof. Sibillé chaired the 2007 European Wireless Conference in Paris and cochaired the TPC of the 2008 IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC). He was a national delegate in COST 273 European cooperation action “Towards Wireless Broadband Multimedia Networks” and is currently Chair of WG2 “Radio Channel” within the ongoing COST 2100 European Action “Pervasive Mobile & Ambient Wireless Communications.” He is also involved in URSI-France as Vice Secretary General and Vice Chair of Commission C Signals and Systems.


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Moe Z. Win (Fellow, IEEE) received the B.S. degree (magna cum laude) from Texas A&M University, College Station, in 1987 and the M.S. degree from the University of Southern California (USC), Los Angeles, in 1989, both in electrical engineering. As a Presidential Fellow at USC, he received both an M.S. degree in applied mathematics and the Ph.D. degree in electrical engineering in 1998.

He is an Associate Professor at the Laboratory for Information and Decision Systems (LIDS), Massachusetts Institute of Technology (MIT), Cambridge. Prior to joining MIT, he spent five years at AT&T Research Laboratories and seven years at the Jet Propulsion Laboratory. His main research interests are the applications of mathematical and statistical theories to communication, detection, and estimation problems. Specific current research topics include location-aware networks, measurement and modeling of time-varying channels, design and analysis of multiple-antenna systems, ultrawide bandwidth (UWB) systems, optical transmission systems, and space communications systems.

Prof. Win has been actively involved in organizing and chairing a number of international conferences. He served as the Technical Program Chair for the 2006 IEEE Conference on Ultrawideband, the IEEE Communication Theory Symposia of the 2004 International Conference on Communications (ICC) and the 2000 Global Communications Conference (Globecom), and the 2002 IEEE Conference on Ultrawideband Systems and Technologies; Technical Program Vice-Chair for the 2002 IEEE International Conference on Communications; and the Tutorial Chair for 2009 ICC and the 2001 IEEE Semiannual International Vehicular Technology Conference. He served as the Chair (2004–2006) and Secretary (2002–2004) for the Radio Communications Committee of the IEEE Communications Society. He is currently an Editor for the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. He served as Area Editor for Modulation and Signal Design (2003–2006), Editor for Wideband Wireless and Diversity (2003–2006), and Editor for Equalization and Diversity (1998–2003), all for the IEEE TRANSACTIONS ON COMMUNICATIONS. He was Guest-Editor for the 2002 IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS Special Issue on Ultra-Wideband Radio in Multiaccess Wireless Communications. His recognitions include the Office of Naval Research Young Investigator Award (2003), the U.S. Presidential Early Career Award for Scientists and Engineers (2004), and the Laurea Honoris Causa from the University of Ferrara, Italy (2008). His papers have received numerous awards including the IEEE Antennas and Propagation Society’s Sergei A. Schelkunoff Transactions Prize Paper Award (2003) and the IEEE Communications Society’s Guglielmo Marconi Best Paper Award (2008). In 2004, he was named Young Aerospace Engineer of the Year by the American Institute of Aeronautics and Astronautics (AIAA), and he received a Fulbright Foundation Senior Scholar Lecturing and Research Fellowship, and an Institute of Advanced Study Natural Sciences and Technology Fellowship. He was honored with the IEEE Eric E. Sumner Award (2006), an IEEE Technical Field Award, for “pioneering contributions to ultrawide band communications science and technology.” He is an IEEE Distinguished Lecturer and an elected Fellow of the IEEE, cited for “contributions to wideband wireless transmission.”