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Where Is the Tag?

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Radio-frequency identification (RFID) has penetrated logistics, manufacturing, production, ticketing, access control, baggage tagging and various other areas of our daily life [1]. RFID technology has experienced tremendous growth and development since its humble beginnings back in the 1940s [2]. These remarkable technical advances have resulted in enhanced performance and novel application areas, which in turn stimulate new needs and spawn exciting new research initiatives. A current hot research topic in the RFID field is RFID localization [3], [4].

In this article we present a broad overview of RFID localization developments and trends. In this context, we use RFID to denote a system that is primarily intended for the identification of an object tagged with a transponder. The basic functionality of an RFID system is a bilateral interaction between a reader and a single transponder. The reader incorporates most of the power-consuming signal generation and signal processing capability. Reader and transponder comprise a single antenna or an antenna array. Transponder complexity is limited because its price and power consumption are critical for most applications. Up to now passive

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and chipless RFID transponders meet this requirement best [1], [5]. However, many custom applications use semi-passive and active transponders, too [6], [7].

We have chosen the above definition of the RFID localization system to differentiate the scope of this article from other publications dealing with wireless local positioning systems (Figure 1). In a wireless local positioning system, localization and tracking is the primary intention, with localization relying on a network of several spatially distributed transceivers or transponders [8]. Multilateration and multiangulation are typical localization techniques used in wireless local positioning systems [9]–[13]. While many basic wireless local positioning techniques are very similar to those used for RFID localization, system and component layouts and target applications are different.

RFID localization relative to a reader can be broken down into two different tasks: ranging and direction finding. A system with both of these capabilities can provide two-dimensional (2-D) or three-dimensional (3-D) localization and an RFID system with only one of these capabilities can still provide useful functionalities.

The ranging and direction finding functions come to us from radar technology [14] and we will subsequently see that many RFID localization solutions are based on radar principles.

Usage and Application of RFID Localization

Distance Bounding for Secure RFID Authentication and Access Systems

Standard RFID systems are vulnerable to relay attacks [15]. During a relay attack an attacker uses two transceiver relay stations to relay the information exchanged between a reader and an RFID tag during a cryptographic challenge-response protocol communication. One relay transceiver powers up the RFID tag and enables contact with the reader. The other relay transceiver communicates with the reader. As the relay can bridge long distances the unauthorized authentication is difficult to detect by the holder of the RFID device. As presented in [15] and [16] it is impossible to impede relay attacks effectively by countermeasures based solely on cryptographic protocols that operate at higher layers of the RFID protocol stacks. Hancke stated: "The only effective defense are distance-bounding or secure-positioning protocols that are tightly integrated into the physical layer of the communication protocol, so as to obtain high-resolution timing information about the arrival of individual data bits."

Distance bounding and the relay attack in passive keyless entry systems and car starting systems attract a lot of attention [17], [18]. Hands-free computer systems, terminal access systems or automatic door openers for buildings are just some of the applications posing similar challenges.

Automatic Range-Dependent Functionalities

If objects or persons equipped with RFID tags are detected in designated zones, automatic responses like opening doors in garages, turning on lights or signaling alarms can be triggered. Some of these ideas have been applied in practice and are commercially available. More examples are automated parking lot access and payment [19] or a system that recognizes the presence of infants in a car and deactivates air bags or issues an alarm signal if children have been left in a car in a dangerous situation—for example, if the temperature in the car reaches dangerous levels [20]. Another application is booting and logging on/off computer terminals [21]. Localization of long-range RFID tags could improve ease of operation by improving reading range and security as users can leave their IDs in their pockets.

Load/unload detection for industrial trucks and the correct identification of loaded items in warehouse management systems is one of the key functions in automatic stock localization. Because of the long reading range of UHF RFID tags it has become a challenge to identify only the loaded item and the precise time of loading/unloading in order to establish the location of the item for the inventory control system.

Locatable long-range RFID tags can potentially improve and broaden the scope of these functionalities by more precisely determining the "trigger zone."

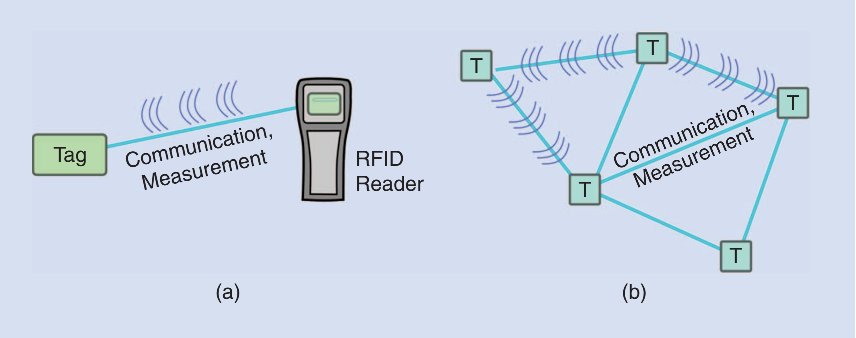

Figure 1. *The main differences between (a) RFID-like localization systems and (b) wireless local positioning systems are lower transponder complexities and the absence of a transponder network.*

Software-Defined Boundaries of the Detection Volume

If RFID is applied in environments where multipath fading and shadowing are to be expected, it is necessary to provide a considerable margin in the link budget to ensure transponders in the vicinity of the reader are correctly identified. Path loss and thus, reader detection range, can vary drastically with time or location. If the path loss is low a tagged object may be identified that is not in the vicinity of the reader and is, in fact, not part of the process. In this case false conclusions may be drawn.

Standard RFID systems feature only coarse locating capabilities with a granularity given by the dimension of a cell formed by a reader. The cell is irregularly shaped and its bounds may vary with time. To assure a spatial and situational context it is common practice to place readers with short reading ranges at key locations, such as at gates and in selected storage areas. However, with increasing reading range this approach becomes more and more impractical.

Only if the RFID system features a ranging capability is it possible to define a maximum reading range per software independently of a link budget margin. With RFID localization, detection areas and volumes can be defined and the benefits from an improved RFID reading range can be exploited as depicted in Figure 2.

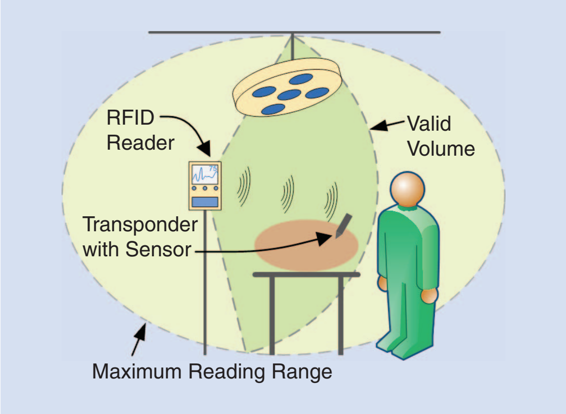

Figure 2. *Automatic range-dependent pairing of remotely readable medical sensors in the vicinity of a reader can prevent incorrect assignments. Ranging as well as direction estimation is needed in this example to check the valid volume.*

Generating Spatial Object Maps for Precise Real-Time Inventory and Augmented/Virtual Reality Applications

If tags can be localized in 2-D or even 3-D, a completely new and exciting application area opens up. A mobile reader capable of localizing RFID tags can build an object map of its surroundings. If the reader is moved it can add areas to its map and its application range can be extended beyond the reader's actual reading range. This is similar to the simultaneous localization and mapping (SLAM) approach [22]. Reference tags can provide a framework for reliable reader localization. A position-aware reader can generate an inventory of all tags and instantly put them in the spatial context. When sufficient spatial information is available, operators can be guided to items of interest using augmented-reality enabled devices that create a common spatial context of operator and tagged items and provide guidance in an intuitive and efficient way.

Furthermore, the data from false positive identifications which heretofore had to be suppressed can now be used. In its spatial context a false positive is additional data which is easy to distinguish from the intended data. Consequently, the additional data can be used for inventory verification and correction or for security purposes. Correct location of hazardous goods can be verified and blocked pathways reported. Large areas inside production facilities can be scanned by antennas mounted on cranes or vehicles to gather additional information. Hospital operating rooms can be scanned to monitor the presence and correct location of vital equipment.

Finding and Retrieving Tagged Objects or Persons

The fact that an item is present might be sufficient information for a stock inventory system; it is most certainly inadequate for a production planning system. The steel billets in Figure 3, for example, might all be known to the inventory control system but with standard RFID systems the most accurate positional information available is the cradle number where a steel billet has been stored.

Therefore a production planning system has to assume the worst-case time needed to retrieve a billet for scheduling purposes and the billet cannot be retrieved automatically. By attaching low-cost tags to items that can be localized by the reader, operator search times can be reduced drastically. Finding tagged objects—especially small objects in densely tagged environments such as shelves—can be speeded up and object retrieval checked automatically [23].

Tagging metal objects as shown in the example above is requested as steel producers strongly want to benefit from RFID technology. Proximity to metal surfaces detunes RFID tag antennas, shifts the resonance frequency and lowers its amplitude. Consequently,

Figure 3. *A cradle of steel billets implies only vague positional information. By individually tracking the billets' locations search times can be cut and optimized storing strategies can be implemented. Metal objects pose additional challenges to UHF RFID systems.*

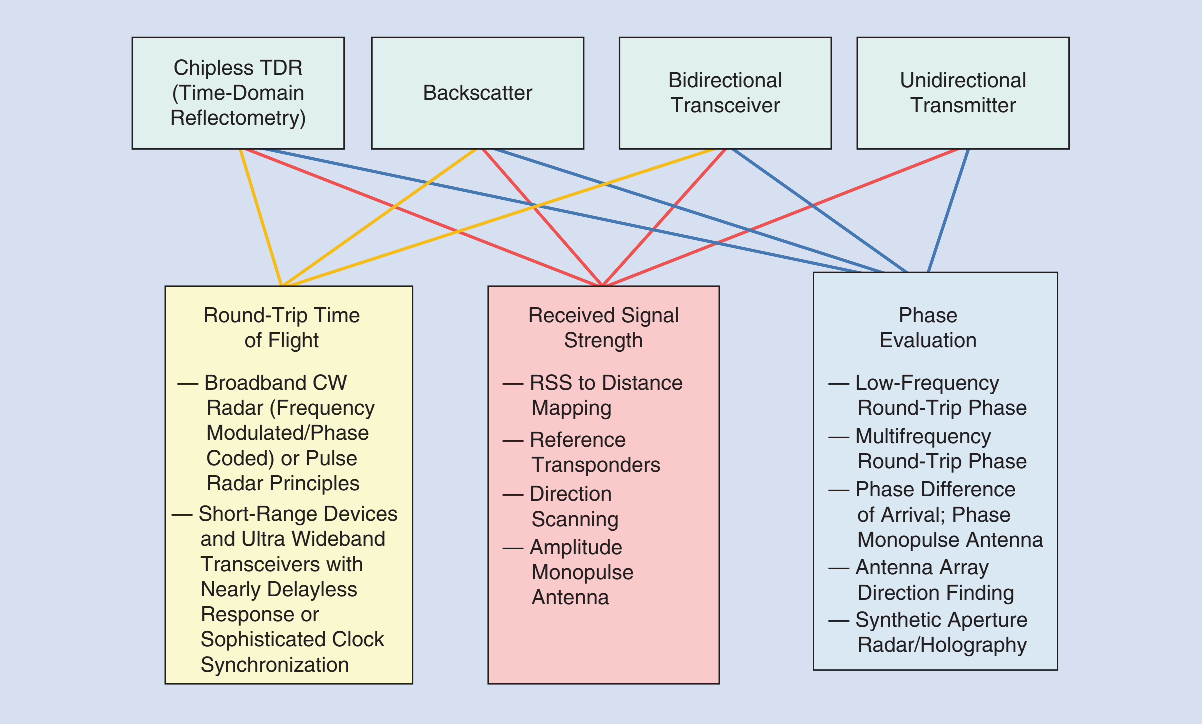

Figure 4. *Classification of RFID ranging techniques. The boxes on the top represent the transponder types used for RFID. As the lines illustrate, almost every transponder type can be used with all three measurement principles.*

the reading range of detuned tags is reduced. Special on-metal tags are commercially available [24]. While some older on-metal tags solemnly rely on a gap between metal surface and tag antenna in the order of 10–20 mm, recently developed tags are tuned to perform very close to metal surfaces [25].

RFID is used for maintenance purposes mainly to reliably identify system components—for example, for maintenance work on airport fire security equipment like fire shutters, fire doors and smoke detectors [26]. It is also used to find these components in complex environments. If numerous tagged components are packed densely together or stowed behind hatches in airplanes, for instance, localization will help maintenance personal work more efficiently.

Passive radar reflectors and active beacons are used by avalanche rescue services [27]. Radar reflectors require custom equipment, and beacons available on the market are difficult to use. Improved localization technologies can potentially reduce search and rescue times and save lives.

RFID Localization Techniques

Classification of RFID Localization Techniques

RFID ranging techniques may be categorized according to three criteria. The first and second are the type of transponder and the fundamental principle behind tag localization. The transponder types are chipless time-domain reflectometry (TDR), e.g., surface acoustic wave (SAW) transponders; backscatter transponders, e.g., UHF RFID tags; bidirectional transceivers; and unidirectional transmitters. Measurement principles are round-trip time of flight (RTOF), in which the time a signal needs to travel between interrogator and transponder is retrieved; received signal strength (RSS), utilizing the relationship between signal strength loss and distance; and phase evaluation, which allows the distance to be determined as a fraction of the signal wavelength, whereby the total number of signal periods is unknown. The third criterion is the actual technique applied based on one of the three principles. Not all of these methods are suited for use with all types of transponders; this is shown with colored lines in Figure 4.

The most important limitations influencing the localization performance of the various techniques are summarized in "Constraints on Performance and Localization Accuracy."

Round-Trip Time of Flight Principles

For an RTOF measurement the reader transmits a signal to the RFID transponder at time $t_{1\mathrm{TX}}$. The transponder retransmits a response to the reader after a predefined processing period $\tau_{2\mathrm{p}}$ that must be known by both units. The time of flight (TOF) to the tag and back to the reader are denoted as τ_{12} and τ_{21}. The basic principle and timing are illustrated in Figure 5.

Given the transmit time $t_{1\mathrm{TX}}$ and the measured receive time $t_{1\mathrm{RX}}$, the reader can calculate the distance to the transponder as

Constraints on Performance and Localization Accuracy

There is a multitude of constraints on RFID localization systems—constraints that may prohibit reasonable usage because of inadequate accuracy levels, complex transponder hardware or additional expensive infrastructure.

One major challenge for all localization techniques is multipath propagation. When the impulse response of a real channel is recorded, an echo profile like the one shown in Figure S1 is frequently encountered.

Strong multipath reflections from the ceiling, the floor and from metal objects coupled with a blocked line of sight between reader and transponder often occur in industrial environments, such as warehouse gates. Therefore, time of flight (TOF) measurements can fail to deliver accurate distance estimation if, for example, the LOS echo is masked by noise or a strong multipath echo. The same applies to received signal strength-based techniques. Reflections can lead to interference which increases or decreases signal strength regardless of the distance, while a blocked line of sight reduces signal strength and leads to greater distance estimations. This can even happen with a clear, unobstructed line of sight in an open space when ground reflections severely impact the measured signal strength (see Figure S2). Note that two measurements with the same tag are very similar as long as the environment does not change. Many of the systems mentioned above utilizing reference tags are based on this fact.

The measured phase is altered by superposition of different signal paths as well. Furthermore, the phase of the transponder signal depends on the modulation properties of the transponder which again depend on carrier frequency and transponder power level [75], [79]. Compensation and calibration techniques are available.

Multipath perturbation effects can be counteracted to some extent by using a higher bandwidth. The minimum width of an echo and thus the range resolution δ_{rad} quantifies the ability of a radar to separate two closely spaced echoes. It is directly linked with the radar signal bandwidth B via:

$$\delta_{\text{rad}} \approx \frac{c_0}{2B}, \qquad \text{(S1)}$$

where c_0 is the free space RF signal phase velocity.

An investigation focusing on the impact of the available bandwidth in a real world RFID scenario is presented in [28].

The plots in Figure S3 show that the ranging uncertainty is on the order of some decimeters if the radar bandwidth is 80 MHz. Achievable accuracies may be considerably worse in severe multipath scenarios—especially if the line of sight is damped or blocked. Typically, the ranging uncertainty is inversely proportional to the radar bandwidth B as predicted by the rule of thumb (S1).

A well-designed system operating in an environment with low-multipath distortion, however, delivers much better ranging precision. An expression for the lower bound of precision σ_r in ideal situations—where multipath and all other distortions, except noise, is negligible—can be derived from the Cramér-Rao Lower Bound (CRLB) [80].

$$\sigma_r(B, E_s, N_0) \geq \frac{c_0}{2B}\sqrt{\frac{1}{\pi^2 E_s/N_0}\left(1+\frac{1}{E_s/N_0}\right)}, \qquad \text{(S2)}$$

where E_s and N_0 denote the signal and noise power. Provided that the bandwidth is fixed by

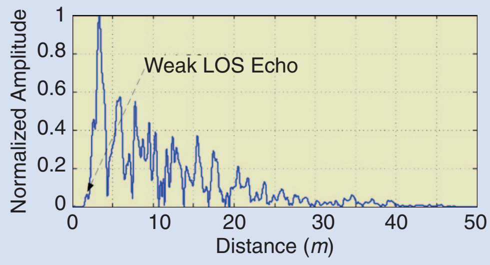

Figure S1. *Echo profile with weak line of sight and extensive multipath components [28].*

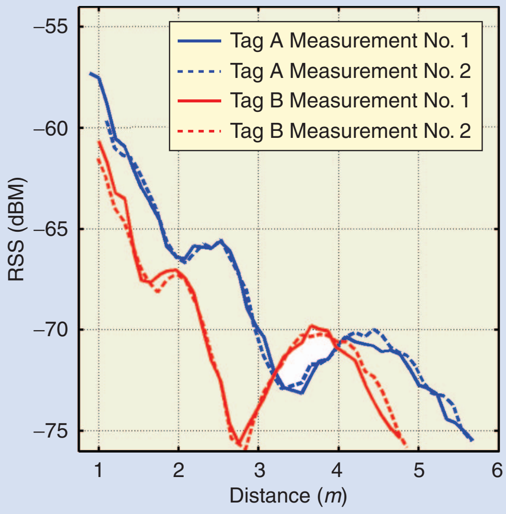

Figure S2. *Multipath fading can cause large differences in field strength. The plot shows received signal strength versus distance in a direct line of sight situation. Tag B is placed 0.2 m below tag A.*

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