Real-Time Location System Asset Tracking Using Wireless Networks

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Abstract – *This work presents a wireless networking–based (Wi-Fi) infrastructure, with accompanying tags, to provide asset tracking in an industrial automation/manufacturing setting. The general principles described in this paper are applicable for most wireless technology variants used for asset tracking.*

1. OVERVIEW: CHALLENGES OF INDUSTRIAL AUTOMATION/MANUFACTURING ENVIRONMENTS

The subject of an asset's location, which was originally associated with the radio-frequency identification (RFID) world, has moved into the more appropriate arena of real-time location systems (RTLSs). RFID is essentially a database management system that uses passive/active/semi-active tags and associated readers to inform the database as to where and when a tag was last observed; RTLS, on the other hand, is an active system that provides real-time tracking of devices. A wide range of wireless technologies can be used to provide industrial RTLS functionality, and certain technologies and techniques are more developmental than others, and new advances frequently enter this space.

An industrial setting presents specific RF and ambient environmental conditions that could be more challenging for a wireless system than most other sites. In a typical manufacturing facility (example shown in Fig. 1), the reflective and absorptive surfaces can lead to variable attenuation and multipath conditions that lead to performance requirements for the wireless devices to operate in non-line-of-sight environments. This combination places considerable strain on the performance, reliability, and maintenance of the components that comprise an RTLS.

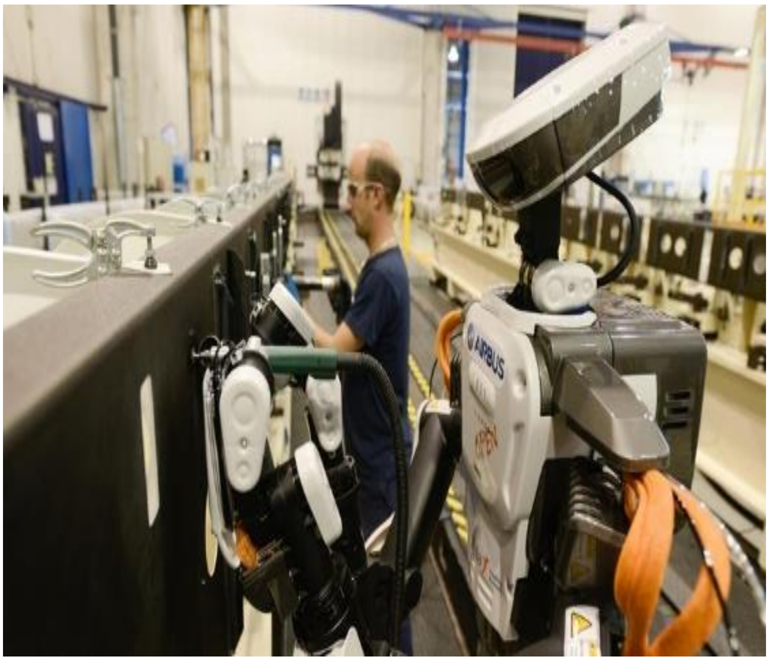

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Fig. 1. Asset tracking in manufacturing and industrial settings such as these shown.

In practice, a radio signal might encounter many objects in its transmission path that could cause additional signal attenuation, depending on the absorption characteristics of the objects. Many objects, including fixed, mobile, and transient items, can absorb RF energy and cause RF attenuation. Because several RTLS techniques rely on the received signal-strength (RSS) value and involve wireless devices operating at various frequencies, such variations in the RF environment can wreak havoc on the system's performance and reliability.

For example, similar to free-space path loss, materials attenuate high frequencies more than low frequencies. From a practical Wi-Fi-based perspective—with few exceptions—5 GHz RF signals typically have higher attenuation than 2.4 GHz transmissions. Although not representative of all materials found in a manufacturing setting, Table 1 shows the attenuation (dB) introduced by several objects and materials to RF signals at the 2.4 and 5 GHz bands. Of particular note is the attenuation values for concrete, which is widely used in industrial facilities. The disparity in the values arises from different types of concrete materials used in different parts of the world. The thickness and coating also differ depending on whether the concrete is used in floors or interior or exterior walls. Brick walls usually have attenuation at the lower end of the range.

Table 1. Typical attenuation values for various materials used in industrial settings

Material	**Attenuation (dB)**	
Frequency band	**2.4 GHz**	**5 GHz**
Interior drywall	3–4	3–5
Material/Cubicle wall	2–5	4–9
Wood door (hollow-solid)	3–4	6–7
Brick/concrete wall	6–18	10–30
Glass/window (not tinted)	2–3	6–8
Double pane coated glass	13	20
Bullet-resistant glass	10	20
Steel/fire exit door	13–19	25–32

Measurements of signal attenuation caused by water, as shown in Fig. 2, reveal higher relative attenuation in the 5 GHz industrial, scientific, and medical bands than in the 2.4 GHz range. In addition, the attenuation effects caused by rain and fog vary with RF carrier frequency. For example, signals in the 2.4 GHz bands can be attenuated by as much as 0.08 dB/mi. by torrential rain (i.e., rain at a rate of 4 cm./hr), and thick fog produces attenuation up to 0.03 dB/mi. Torrential rain can produce attenuation up to 10× higher at 5.8 GHz (0.8 dB/mi.) than at 2.4 GHz. Similarly, thick fog attenuated the 5.8 GHz signal by up to 0.11 dB/mi. In addition, human bodies, which are predominantly composed of water, attenuate RF signals by approximately 3 dB in the 2.4 GHz range and by 5 dB in the 5 GHz range. Additional information regarding signal attenuation for 2.4 and 5.8 GHz can be found in "Propagation Losses: 2.4 GHz vs. 5 GHz" 2002 Magis Networks, Inc., which can be found at the following link:

http://www.am1.us/Papers/E10589%20Propagation%20Losses%202%20and%205GHz.pdf.

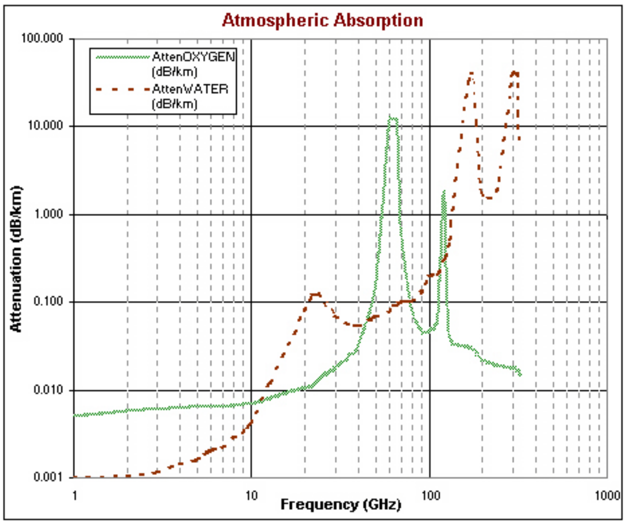

Fig. 2. Attenuation values of oxygen and water [6].

Understanding these attenuation differences is key to signal strength–based location determination, and care must be taken in situations in which a mobile tag might be traversing an area that contains these differing materials. From a signal intensity perspective, an intensity decrease caused by different materials could be misinterpreted as a distance/location variation.

2. Asset Tracking Using Wireless Technologies

Several RTLS techniques are based on changes in the asset tag's radio signal strength and associating that signal strength variation with a change in the separation distance between the access point (AP) transmitter and the asset tag's receiver. Signal strength decays as the receiver and transmitter move farther apart. This fundamental principle is based on the $1/R^2$ electromagnetic field law, sometimes referred to as the inverse square-law. In terms of communication systems, this means that the RSS follows line of site, as expressed in Eq. (1):

$$\text{RSS proportional}1/R^2, \tag{1}$$

where R is the receiver-transmitter separation distance. The RSS decreases as $1/R^n$ in most situations.

In this scenario, the variation in RSS is predicated on all other parameters remaining constant; with that holding true, any variation must be caused by a change in distance between receiver and transmitter. If the receiver can measure or have a priori knowledge of the transmitter's output level, then the distance, R, can be determined. This leads to contour lines in the AP's signal strength (Fig. 3). The asset tag's wireless transmitter may then transmit its associated RSS value (along with its unique radio/tag ID) to the AP. That information is then processed locally on the wireless networking RTLS AP (if the AP has that computational capability) or passed on to a software application for it to determine the location of the tag with respect to the (typically) fixed location of the AP.

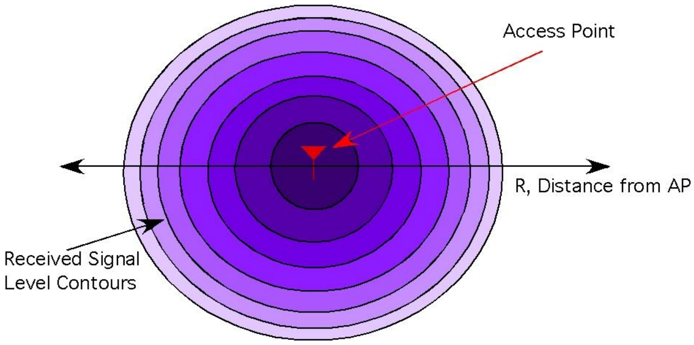

Fig. 3. The RSS decreases as $1/R^2$ with separation distance leading to the diagram's signal strength contour lines.

The asset tag's RSS value can be used to determine the asset's distance, in radial coordinates, within a certain range of the AP—the distance is known but not the angle. Determining the X, Y, and potentially Z coordinates of the tag requires the tag to be within communications range of at least 3 APs.

RSS-based techniques have been applied using several wireless technologies. As expected, the frequencies used by these different technologies also vary. Following Table 1, this implies that the RSS value within a single facility—relative to the actual transmitted signal level—will be different for the different facility constituent materials. The typical RTLS implementation is depicted in Fig. 4. For ease of discussion, the accompanying descriptions are based on RSS and an IEEE 802.11 (Wi-Fi) infrastructure.

For improved location determination, the AP's transmission power should be reduced to shrink its individual RF footprint. More APs can then be deployed in a denser array, with each additional AP gathering valuable location data.

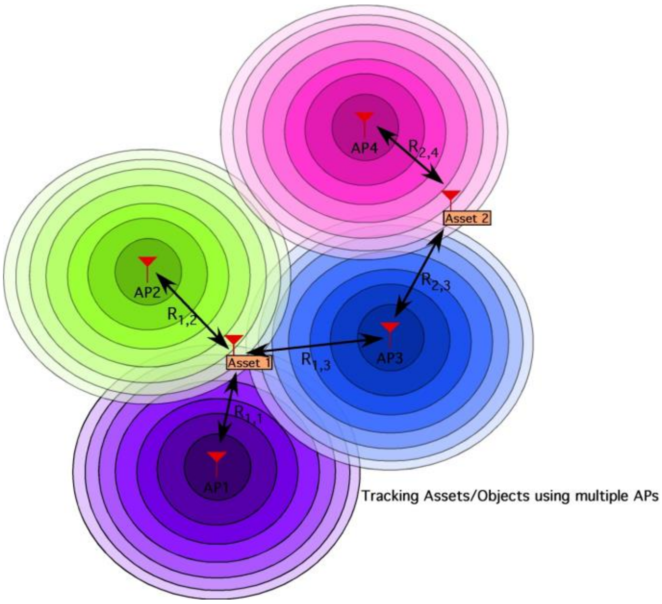

Fig. 4. RTLS positional information for the asset tag. Using RSS requires the tag to be within range of multiple APs.

3. Location Determination

Several techniques can be used in location determination and tracking. Principal among them is the time difference in arrival approach. This method requires an infrastructure of fixed APs, and the signal from the asset tag arrives at the individual APs at different times. The differences in each arrival time can then be used to calculate the asset tag's location.

To track the asset tag using fixed APs, one must determine the four variables associated with the tag: its three position coordinates, A_x, A_y, and A_z, and the time of the determination, A_t. As basic algebra instructs, solving for four variables requires four equations and performing a simultaneous solution. AP-based tracking can operate from a beacon pulse (signal) emitted simultaneously from the APs, with the asset tag receiving signals from at least four AP sources and measuring the time required for the signals to arrive at the tag. Each AP has a unique identifier that can provide the tag with a means of identifying the received signals.

Alternatively, the asset tag can emit a beacon pulse at a predetermined interval. The beacon pulses arrive at each AP at slightly different times depending on the distance from the asset tag to the AP. Using the simple equation $R = V * t$, where V is the velocity of the signal (speed of light), t is the time required to receive the signal, and R is the range from the tagged asset to/from the APs.

Knowing the location of an asset tag relative to several terrestrial APs might be sufficient if a tag stays within the bounds of a local array or network, often within a building. However, if an asset tag is to travel outside or between these local arrays, then the implementation of GPS-based tracking is essential for determining the asset tag's location. Within the signal transmitted from the GPS satellite are its X, Y, and Z coordinates at the time that the signal was sent. Having this positional information for four GPS satellites—coupled with the range between the asset tag's receiver and each satellite as well as the clock bias (C_b) information—yields the four equations, Eqs. (2–5), necessary to determine the location of the asset tag.

$$(X_1 - A_x)^2 + (Y_1 - A_y)^2 + (X_1 - A_x)^2 - (R_1 - C_b)^2 \tag{2}$$

$$(X_2 - A_x)^2 + (Y_2 - A_y)^2 + (X_2 - A_x)^2 - (R_2 - C_b)^2 \tag{3}$$

$$(X_3 - A_x)^2 + (Y_3 - A_y)^2 + (X_3 - A_x)^2 - (R_3 - C_b)^2 \tag{4}$$

$$(X_4 - A_x)^2 + (Y_4 - A_y)^2 + (X_4 - A_x)^2 - (R_4 - C_b)^2 \quad (5)$$

With simultaneous data received from four APs, the asset tag's location (e.g., latitude, longitude, altitude, and time) can be calculated. Under ideal conditions, specifically direct line of sight to the APs (no multipath) and—for exterior locales—minimal atmospheric-induced variations,[1] the location is precisely and accurately determined. GPS-based asset tracking is represented in Fig. 5.

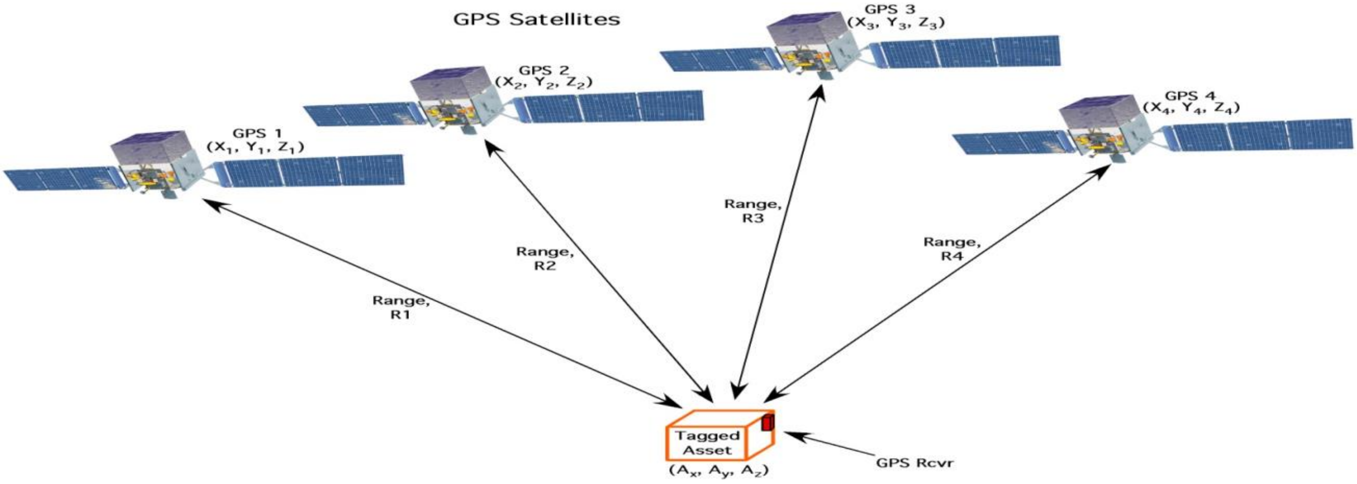

Fig. 5. GPS-based asset tracking requires the receiver to be "visible"within line of sight to four GPS satellites.

An industrial environment is not ideal for a Wi-Fi-based asset tracking system. An asset tag's visibility to four APs and the multipath environment present in industrial and manufacturing settings might cause considerable degradation of the beacon signals, which is particularly troublesome when trying to ascertain the clock bias. In terms of GPS-based tracking, nonrestricted signals are transmitted at 1.575 GHz, a frequency that is essentially blocked by steel and concrete structures (e.g., buildings and tunnels) and attenuated by trees and leaves.

A measurement based solely on intensity could be problematic because any change in the RSS might be interpreted as a change in separation distance between the AP and the asset tag, but the variation could actually be caused by a defect in the equipment or a change in the environment (e.g., decrease in the transmit power, decrease in the receiver sensitivity, introduction of a new object that attenuates the signal). Although a change in RSS could degrade asset location accuracy and performance, an asset tag's location is still provided with a measure of variation based on the change in the network. Also, RSS-based asset tracking is not measured in specific units, and this lack of standardization presents another problem. Each wireless device vendor uses an arbitrary set of numerical units that are specific to their equipment. For example, attempting to match a given RSS value with a power unit such as megawatt leads to serious problems if devices from multiple vendors are supposed to interoperate.

RSS is also relevant to Wi-Fi applications of all types because much of the perceived performance of a wireless network is based on inferences made using RSS. For example, client devices can monitor the RSS on a particular channel (frequency) and make decisions accordingly: the higher the RSS value, the higher the transmit data rate (up to a maximum); so if the RSS value drops below a certain threshold, the device assumes that the channel is clear to send and transmits data. The association and disassociation of client roaming between multiple APs is also almost entirely determined by RSS. Although RSS might not provide the optimum asset tracking capability, it is still used for a wide range of client-host operations. Figure 6 illustrates this scenario in which directional antennas are used.

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[1] Radio signal velocity is given by $V = c \div n$, in which c is the speed of light (constant). Variations in V could arise from changes in the index of refraction, n, which itself differs for various atmospheric densities caused by changes in humidity, pressure, winds, and so on.

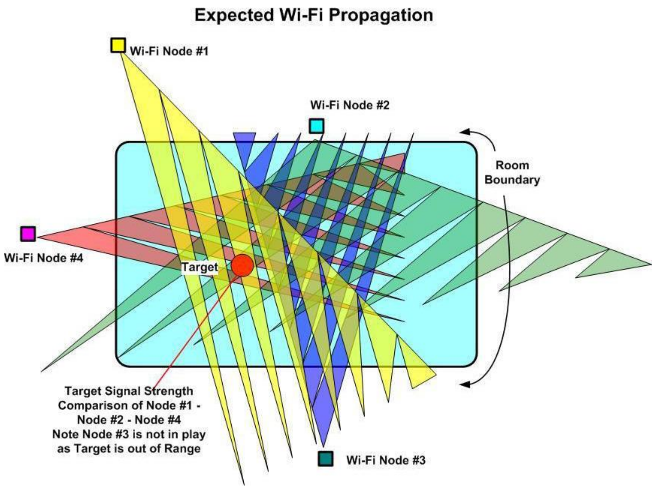

Fig. 6. Spatial resolution is provided in multiple axes only if the asset tag (labeled *Target* in this figure) is communicating with multiple APs.

Infrastructure requirements for a Wi-Fi RSS-based asset tracking system are not dissimilar to requirements for conventional wireless networks that transmit data or voice communications. Wi-Fi-based asset tags are managed as any other wireless client, with the exception that voice and data solutions are provided network priority to maintain quality of service and production application availability. To meet these requirements, such asset tags are maintained on separate virtual local area networks to maintain separation from production wireless applications.

State-of-the-art deployment tools can verify that the infrastructure requirements are met, and—for cases in which the requirements are not met—problem areas are indicated and recommended solutions are provided. A typical VoIP wireless network provides excellent location granularity, and at least one solution provides software clients for tracking VoIP phones.

4. RF in a Manufacturing Facility

Although the RF footprint is obviously dependent on the transmit power and antenna gain (directionality), the typical indoor-specified, Wi-Fi-compliant range is about ~40 meters. For a large facility, this value is mapped into the geometry of the actual location, which results in a coverage map similar to the one shown in Fig. 7. Though vendors differ in the RF channel assignments for the Wi-Fi APs, consistency is needed in terms of over-the-air security and ease of tag-to-AP association as asset tags roam through the automation facility.

RF signal coverage and density are essential elements for a functional wireless network. In particular, RSS and the number of APs located throughout the facility are two of the most critical determining factors for tracking accuracy. However, regardless of the density and RSS values, all Wi-Fi systems can provide asset location with varying degrees of accuracy— *X*, *Y*, map, zone, or presence functionality. Asset location granularity depends on the wireless environment and on the requirements that each facility has for those critical pieces of equipment.

One advantage of the signal strength–based position tracking solutions is that the RF coverage for RTLS can be easily determined using a location coverage visualization application that is provided with many RF site survey applications. When used in conjunction with the network requirements visualizations, this makes it easy to visualize and report areas of strong coverage and identify areas where the network might be improved for RTLS location accuracy if needed. In essence, some site survey products enable one to manage the wireless network while also providing reporting and planning functions to enable a user to plot location performance for asset tracking.

Even with all the advantages that an RSS Wi-Fi-based tracking system provides, the prospect of potentially thousands of Wi-Fi-based asset tags communicating over a company's wireless network will raise performance and security concerns for the organization's IT department. However, in most cases—specifically for battery-operated devices—the tags communicate only sporadically through the network. Tags that incorporate an integrated motion sensor might be programmed to only "announce" themselves when the tagged asset is moving. Once an object is at rest, the location is recorded, and the tag essentially remains in "sleep" mode until movement is detected.

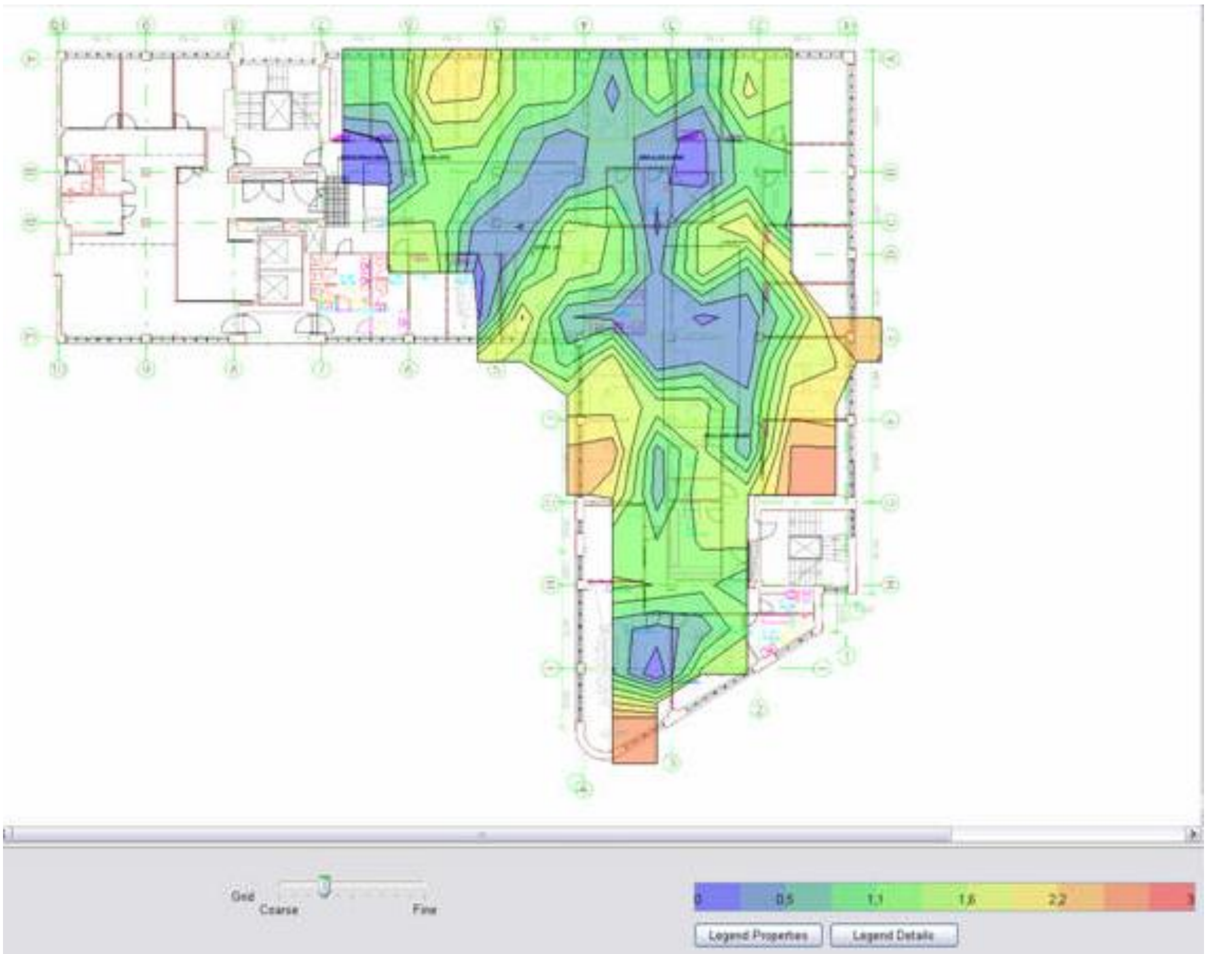

Fig. 7. Predicted Wi-Fi coverage for an office setting. This figure does not differentiate between RF signals from different APs.

To ensure that the Wi-Fi-based asset tags are easy to deploy and AP vendor-neutral, the tags are configured with security settings that are acceptable to the Wi-Fi infrastructure. Using a more robust security setting would require more data to be transmitted to and from the AP, thereby shortening the asset tag's battery lifespan. In certain vendors' cases, a low-frequency (262 kHz) RFID signal could also be used for a wakeup or interrogation/beacon signal with certain tags being dual use in terms of Wi-Fi transmission or active RFID operation.

Using a Wi-Fi beacon tag could reduce issues with battery life and network authentication. In this scenario, the APs in the network—during normal operation—periodically scan the clients (any Wi-Fi device) that are within the network footprint and send this scan information (RSS, media access control address, and timestamp) to the infrastructure's network controller. The controller is instructed to output this information to the appropriate location software, which can then calculate the position of the scanned device media access control addresses using the RSS. In this scenario, the client does not have to associate, with the AP but rather just respond to beacon probes from the network.

The data transfer from Wi-Fi tag to AP is typically accomplished with the User Datagram Protocol, which implies no acknowledgement of transmission receipt, unlike the case with the Transmission Control Protocol. The conventional issues associated with unacknowledged data transmission do arise, but the tag itself is less complex and longer lived (battery operated) by not listening and acting on the acknowledgement (or lack thereof).

5. RF Fingerprinting

Although tracking assets outside of an industrial/manufacturing facility can be problematic because of RF multipath, varying signal propagation and attenuation inside the facility might lead to even greater difficulty in tracking. Signals might propagate from transmitter to receiver via multiple paths by bouncing off walls and other RF-reflective environments, and moving equipment and individuals complicate the issue further.

This variability in signal propagation has led to an area of research referred to as *RF fingerprinting*. The overarching principle is defining RF characterization of the ambient environment based on signal-strength measurements taken when the system is initially deployed. Later, when the system is in use, real-time RF signal-strength measurements are taken by the mobile tags and compared with the baseline RF fingerprint measurements to calculate the location of the tags. More than 30 RF fingerprinting–based localization systems have been proposed by researchers in this field [1–4]. One representative system design and operation is presented in Fig. 8. In this example, the facility is organized into RF blocks, and asset locations are within a given block. Finer spatial resolution of the asset tag locations is achieved by having a higher number of smaller blocks in a denser configuration."

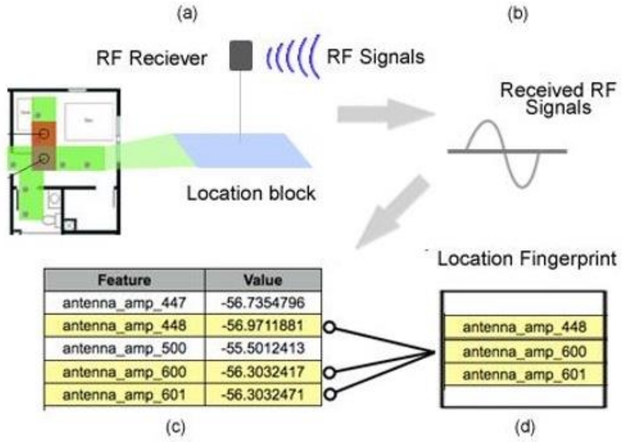

Fig. 8. Generation of a location fingerprint. (a) Signal arrives at an RF receiver in a location block. (b) The received signal data are parsed and preprocessed. (c) The sampled signal data are the potential features. (d) The location fingerprint is a subset of these collected features unique to this location block.

6. Communication Ranging

As previously mentioned, a number of technologies are available to track assets. Having the coordinates of a gateway and then using some type of communications ranging to determine the radio's distance to the gateway is one popular option [6]. Several mesh-networked topologies and associated protocols have also been demonstrated, with each yielding some location information of the wireless device (asset) relative to the gateway. A similar approach is sometimes used for cellular-based RTLS, in which a message is transmitted from numerous base stations (cell towers). In this example, the mobile telephone associates with a cell tower, and—if the tower's location and RF footprint are known—the RTLS-like localization of the mobile telephone is achieved (i.e., the phone is near a certain cell tower). Higher spatial resolution requires more cell towers, each with a smaller RF footprint.

Variations on this approach might use a common message transmitted from several cell towers. If the mobile telephone is within range of at least four towers, then—similar to the AP or GPS simultaneous solution of multiple equations—the location of the mobile telephone can be determined from the different arrival times of the common message sent by the cell towers.

Improvements in cellular technology have enabled increased resolution in asset tracking. The many variations of mobile technology led to differences in the base underpinnings and associated accuracy in location determination. The base stations need to be time-synchronized for mobile-phone ranging using time-of-arrival; this subject is covered extensively in [7].

7. Summary

Several methods are available for determining the location of an asset. As the complexity of the infrastructure increases, the functionality requirements placed on the asset tag decrease. Regardless, the general tag design—illustrated in Fig. 9—might remain the same even as the software complexity changes.

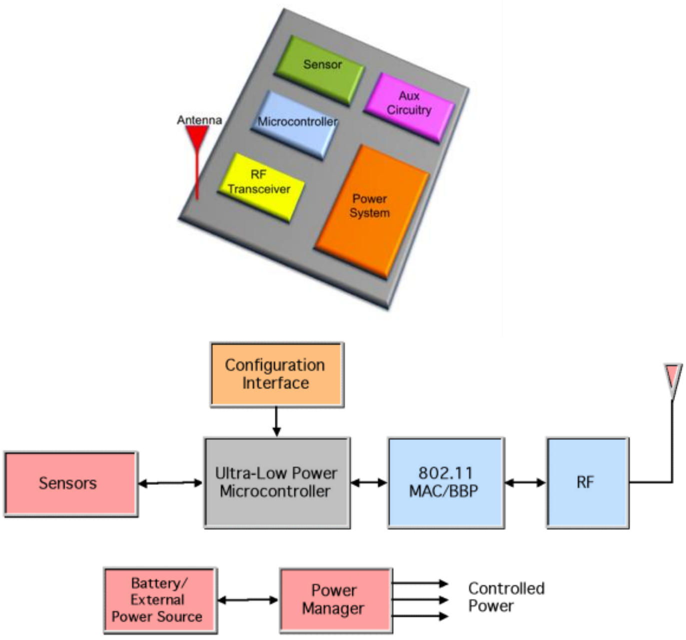

Fig. 9. Generic asset tag tracking design.

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