Indoor Positioning Systems

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Indoor Positioning Systems (IPS) are used to locate medical equipment, patients or staff members inside the hospital. They have existed for almost 20 years, but have only recently become practical to deploy as their cost has come down and performance has increased. Additionally, with the recent publicity surrounding Radio Frequency Identification (RFID) systems, IPS has become more "mainstream" because many people equate IPS to RFID. This article will review the various options that are available for medical IPS and outline some of the trade-offs to consider during the review of such a system. It will also discuss some of the day-to-day maintenance and support issues for the various solutions as well as speculate on some of the future developments that may be in store for the technology.

The fundamental methodology that is used by the IPS to determine a tagged object's location is very important and drives most of the other system parameters. Important system parameters to consider in evaluating an IPS include accuracy, reliability, cost of acquisition, cost of ownership, tag battery life, ease of installation/support/expandability, EMI considerations, tamper/security features and the openness of the system. Therefore, this article will organize the descriptions of the various positioning solutions around the fundamental location methodology they employ.

Current State-of-the-Art

For the sake of this discussion, we will group the currently available IPS into five categories, based on the fundamental technique they use to determine location. These will be: Passive RFID, Active RFID, Infrared, Radio Triangulation and Radio Fingerprinting.

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Figure 1. *Texas Instruments Passive RFID (for access control; range is about eight inches.)*

Passive RFID

Although Passive RFID is not really a location technique, there has recently been a great deal of discussion around the technology. WalMart and the Department of Defense are both rolling out large-scale programs that require their vendors to label products with Passive RFID tags. These tags, as the name implies, were originally developed to provide identification of tagged devices. Location information can be surmised from the location of the transponder that was used to read the data on the tag. The current state-of-the-art allows read ranges of about 8 inches with tags with a price of 50¢ to $1.00 and reader antennas that cost between $300 and $5000. The tags are flat and typically about credit-card size; the reader antennas can be pocket-book size to doorway size. Since these tags are passive (don't have a battery in them) their performance is driven by signal-to-noise ratio concepts. The tag can be smaller, or the read distance can be longer, but then the reader antenna must be bigger. Conversely, a smaller read antenna can be used if the tag is larger. What this practically means is that small (1x2 inch), inexpensive ($1.00) tags can be placed on assets but large (6 x 3 feet), expensive ($3000) receivers must be placed at every door.

The key point here is that these systems don't really provide location at all; since the readers have such a limited range, location is surmised from which reader last read the tag. For example, you likely have a Passive

RFID tag that is used to give you access to certain restricted areas of the hospital; the system knows that you walked through the main door to the operating theater, but once you're in the OR it can't locate you. Typically these systems are only used for entrance to a restricted area and not for exiting the area. Similarly, if large expensive antennas are used on both sides of a door (such as you might see at the exits of a music or clothing store) an asset or person with a passive tag can be detected moving through the door. Once they are through that "portal" their location is no longer known. Another key point is that the large antennas radiate a relatively high amount of RF energy and hence may create EMI concerns.

Troubleshooting and servicing these solutions typically focus on maintaining and tuning the antennas. Since they are relatively large for doorway type coverage, they get battered and detuned quite often. As with any of the systems the integration of the data into the existing hospital information systems is an important and often overlooked ongoing task.

Infrared Based IPS

The oldest systems used for true location are based on infrared (IR) energy. These solutions consist of a tag which transmits IR pulses and receivers placed in every room. Since the IR energy won't penetrate walls, the location of the tag can be determined simply by noting which room a receiver that "sees" the given tag is in. Obviously, receivers must be placed in every location where a person or an asset might be. These systems are quite elegant in their simplicity, but have some fairly serious issues. One is that if the tag gets covered up, for example, by a bathrobe, the patient's body or another asset, the system no longer works; one study surmised that the IR is covered up, and hence the system can't locate, approximately 40% of the time. Another issue is that it takes a lot of energy to light the IR LED, so the tag's battery life tends to be relatively short and the replacement costs can be high. Finally, since an IR receiver is required in every room a tagged object might be in, and that these receivers are connected to the controlling PC through custom wiring and infrastructure, the installation of IR systems is quite invasive, time-consuming and expensive.

IR solutions can provide room-level accuracy. Higher accuracy levels can be achieved by limiting the receiver's reception area and placing more receivers in the area in question. It is impossible to provide zone-level accuracy (where a zone is larger than where the fixed walls of the hospital are) without the IR system having a radio-based fallback system.

When IR systems fail it is usually due to either the battery in the tag dying or the tag getting covered up. There are various concentrators and collectors that are used as part of the receiving infrastructure, but these tend to be reasonably reliable once they are installed. Once again, the location database must be robust and open to serve the needs of the hospital.

Radio Triangulation

The outdoor Global Positioning System (GPS) is based on radio triangulation. GPS signals are too weak to penetrate buildings, so GPS can't be used for indoor location. However, there are some IPS solutions that are based on the same principle. Tags transmit signals (typically at 2.4 GHz) and multiple antennas placed through-

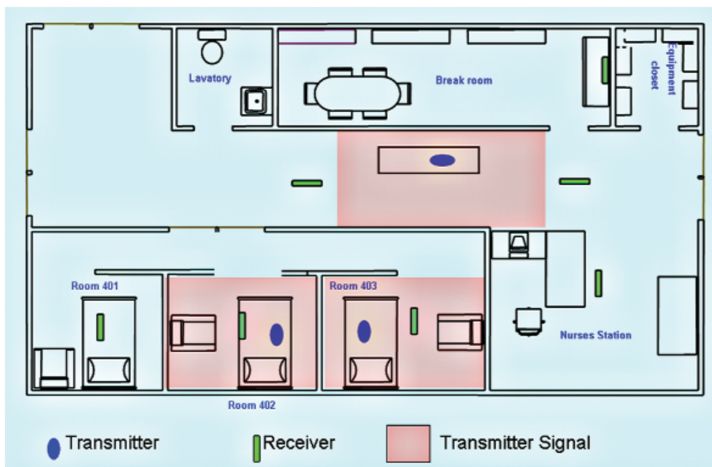

Figure 2. *Infrared Based IPS (pink is where IR signal is received)*

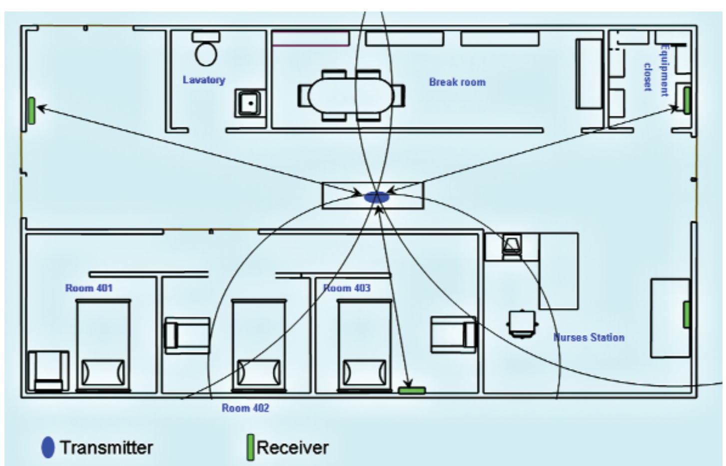

Figure 3. *Radio Triangulation Based IPS (signal travels from transmitter to three receivers)*

out the hospital pick up the transmissions. These antennas are connected back to a receiver that precisely measures the time it took each signal to travel from the transmitter to each of the antennas. Since radio signals travel at the constant, known speed of light, and distance equals rate times time, the distances between the transmitter and each antenna can be calculated. This calculation yields a ring around each antenna; the transmitter must be some place along that ring. Given that the location of each of three antennas are known, the location of the transmitter can be determined by calculating where the three rings, each with one antenna at its center, intersect.

Triangulation systems can be very accurate in large open spaces; indoor inaccuracies are created when the radio signals don't travel in a straight line from the transmitter to the antenna and instead bounce off walls, ceilings and floors (this is called multipath). Various techniques developed to compensate for multipath allow the accuracy of these systemsto be typically 1–3 meters. The big issues with these solutions are their expense and complexity. The speed of light is 300,000,000 meters per second, so to get 1 meter of accuracy the timing of the system must be accurate to about 3 billionth of a second (3 nanoseconds). To accomplish this high degree of temporal precision, radio triangulation systems connect their antennas to precision time bases with coaxial cable. This is very difficult, expensive and invasive to install. The precision timing also drives the high cost of the system, making RF triangulation solutions one of the most expensive to purchase and install. Ultrawideband (UWB) systems are conceptually similar to triangulation systems and are just beginning to be introduced to the market. The batteries in the tags used for triangulation-based systems typically have lifecycles of six to twelve months and are moderately priced.

Troubleshooting triangulation systems is quite subtle. Since a major source of error in the system is multipath, which can change on a minute-to-minute basis, one of the most important aspects of troubleshooting is keeping good records and detective work. Are there more errors when the metal food service carts are in the halls (thus changing the RF environment)? Are there some times of the day that are more problematic than others? Are certain locations more problematic? A good spectrum analyzer and knowledge of basic radio principles are also useful to have. Relative to the other systems described here, radio triangulation and radio fingerprinting are the most difficult to troubleshoot.

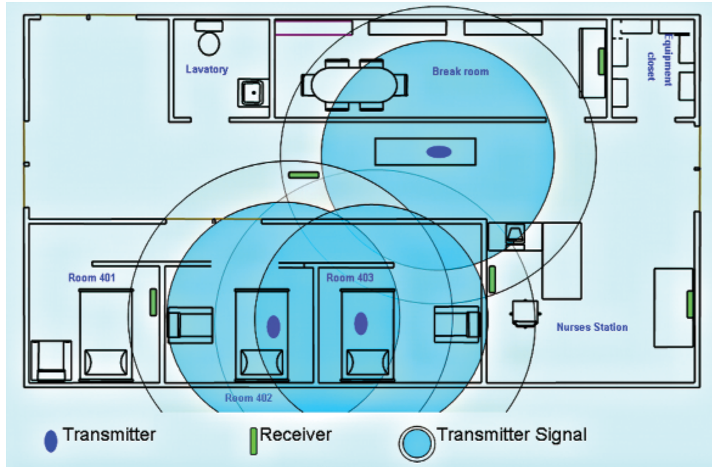

Figure 4. *Radio Fingerprinting Based IPS (receivers learn signal strengths for given locations)*

Radio Fingerprinting

Radio Fingerprinting is a relatively new technique that is based on the assumption that an RF environment doesn't change that much over short periods of time. Standard WiFi wireless transmitters and access points (AP) are used and a site-survey is conducted that records the strength of the radio signal at various locations in the hospital. When the location of one of the standard wireless LAN radios is needed, a computer estimates the location based on what the site survey revealed the RF environment, or "fingerprint" was. The advantage of this solution is that it uses standard APs, so if there is already a wireless LAN installed everywhere a device may need to be located there is very little additional hardware expense. The disadvantages of such solutions include the fact that the devices to be tracked must have a wireless LAN card and they must be turnes on. This typically makes tracking patients, staff and non-networked assets (such as IV pumps) difficult if not impossible. Any stand-alone tag must, by definition, be compliant with the wireless LAN (typically 802.11b) which drives the cost and power demands up. At this point, the software prices for these solutions are still quite high (approximately $200,000 for a 200 bed hospital) and the accuracies of the systems are still being determined.

The troubleshooting and servicing issues surrounding RF Fingerprinting solutions are similar to those of RF Triangulation, with the additional skill required of a good understanding of troubleshooting IT networks.

Active RFID

Unlike passive RFID, active RFID can provide location in addition to identification. Active RFID solutions use an RFID tag that consistently transmits a known signal. The signals are received by receivers that forward the data over a network to a computer that estimates the tag's location based on, among other things, signal strength. The tags have batteries in them, so unlike Passive RFID systems their performance is not driven by antenna size. This means that the receivers are typically quite small. Since they don't typically use time to determine location the precise timing that is required in RF Triangulation systems (and its associated cost) is not necessary. This means that the receivers can plug directly into an existing wired or wireless LAN, which greatly simplifies installation. The systems are typically close to 100% reliable and have scaleable accuracy from a few meters to a zone of ten meters.

The big advantage of Active RFID solutions is their low cost. The complete solution can be only 20% of the cost of an RF triangulation system. The active tags are more expensive than passive tags, but much less expensive than all the other types of tags. However, since the active RFID systems use batteries for their source of power, the receivers that are required are simpler and cheaper than passive RFID receivers. Battery life is measured in years and not months.

Figure 5. *Active RFID Tag (Shown on clinician)*

Troubleshooting Active RFID systems requires a good understanding of IT networks. Since the receivers are simply networked LAN appliances, typical problems involve the assignment of IP addresses, LAN subnets and the like. Active RFID systems represent the most practical solution to indoor positioning.

Future Developments

To date the widespread deployment of IPS has been lim-

	Passive RFID	Active RFID	Infrared	Radio Triangulation	Radio Fingerprinting
Estimated System price per hospital	High	Low	Moderate	High	Low
Network Required	Custom: low voltage & coax	Standard Wireless or Wired LAN	Custom: low voltage	Custom: coax	Wireless LAN
Accuracy	Zone level	Bed, Room or Zone level	Bed or Room level	Bed, Room or Zone level	Room or Zone level
EMI Issues	Up to 1 W transponder power	Insignificant; very low RF power	None	100 mW 2.4 GHz	100 mW 2.4 GHz
Tag Battery Life	No battery	2-6 years	6 months	6 months	2 years
Battery Cost per ID-tag	No battery	23¢/year	$14/year	TBD	TBD
Security	None	Yes	Yes	Yes	None
Dynamic Data	No	Yes	Yes	No	Yes

Table 1. *Comparing Technologies*

ited by their high cost and limited reliability. However, now that active RFID solutions are available that will likely change. Since these systems typically have the lowest costs, they have a very fast payback.

Therefore, as IPS systems become more ubiquitous, one can expect to see more and more applications that exploit these infrastructures. The first applications are focusing on asset tracking. There is also considerable interest in using the systems to increase work-flow through the hospital; in fact, some work on this has already been done. In order to be successful, it will be crucially important that the IPS is viewed as an infrastructure; a resource that is owned by the hospital and can be exploited by all. It will be very limiting if the IPS system can only be used by one vendor. ■

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