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INDOOR GEOLOCATION IN THE ABSENCE OF DIRECT PATH

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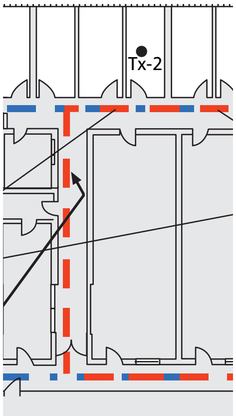


The authors explain the reason for frequent absence of direct path and they introduce and analyze the effectiveness of two novel approaches to mitigating the large ranging errors caused by UDP conditions.

ABSTRACT

Severe multipath in indoor areas causes undetected direct path (UDP) conditions, which pose a serious challenge to the design of robust precision indoor geolocation systems. Based on a scenario on the third floor of the Atwater Kent Laboratory at the Worcester Polytechnic Institute, we explain the reason for frequent absence of direct path, and introduce and analyze the effectiveness of two novel approaches to mitigating the large ranging errors caused by UDP conditions. The first technique exploits nondirect paths for ranging, while the second approach relies on cooperative localization for wireless sensor and ad hoc networks.

INTRODUCTION

In the late 1990s, motivated by a variety of envisioned applications in commercial, public safety, and military settings, indoor geolocation began to attract considerable attention [1, 2]. In commercial applications for residences and nursing homes, there is an increasing need for indoor geolocation systems to track people with special needs, the elderly, and children who are away from visual supervision. Other applications include systems to assist the sight-impaired, to locate instrumentation and other equipment in hospitals, to locate surgical equipment in an operating room, and to locate specific items in warehouses. In public safety and military applications, indoor geolocation systems are needed to track inmates in prisons, and to guide policemen, firefighters, and soldiers in accomplishing their missions inside buildings. More recently, localization has found applications in location-based handoffs in wireless networks, location-based ad hoc network routing, and location-based authentication and security [3]. Given the growing interest in sensor networks and radio frequency identification (RFID) technologies, one can also envision wider-ranging applications such as locating unwanted chemical, biological, or radioactive material using sensor networks, and tracking specific items such as controlled pharmaceuticals in their containers using RFID tags.

The most popular emerging indoor location and tracking systems use information about RF signal properties in large indoor areas. However, location sensing using multiple cameras and ultrasound is also becoming popular for line-of-sight applications within a room. In this article our focus is on achieving precise RF localization in indoor areas, which we call indoor geolocation. To implement low-cost RF localization systems, the target object should be an existing traceable device that radiates RF signals and is connected in some manner to a backbone network. There are tens of millions of IEEE 802.11 WLAN network cards, billions of RFID tags, a growing number of IEEE 802.15 wireless personal area networks (WPANs) using Bluetooth, ultra wideband (UWB), and ZigBee technologies, and several billion cellular phones that are connected in various ways to the Internet and can be used for RF localization. The bandwidths of these devices range from close to 100 kHz in traditional RFID tags to several gigahertz for emerging UWB devices, providing numerous technical opportunities to implement localization systems with various degrees of precision. The accuracy required for indoor localization also depends on the application, and in indoor areas it varies from a few millimeters for locating surgical equipment in an operating room to as much as a few meters for locating a person or an item of equipment inside a specific room in a large building.

RF localization systems locate the target based on the features of the received signal radiated from the device. There are two popular metrics for this purpose: the received signal strength, which is easy to measure but provides less accurate positioning [4], and the time of arrival (TOA) of the direct path, which can potentially provide more accurate localization [1, 2, 5, 6]. This article addresses precise localization using TOA-based systems. Currently, robust precise TOA-based localization in multipath-rich indoor areas has remained a challenge facing the research community. The core of this challenge is to understand the cause of unexpected large ranging errors in estimating the TOA of the direct path between the transmitter and the

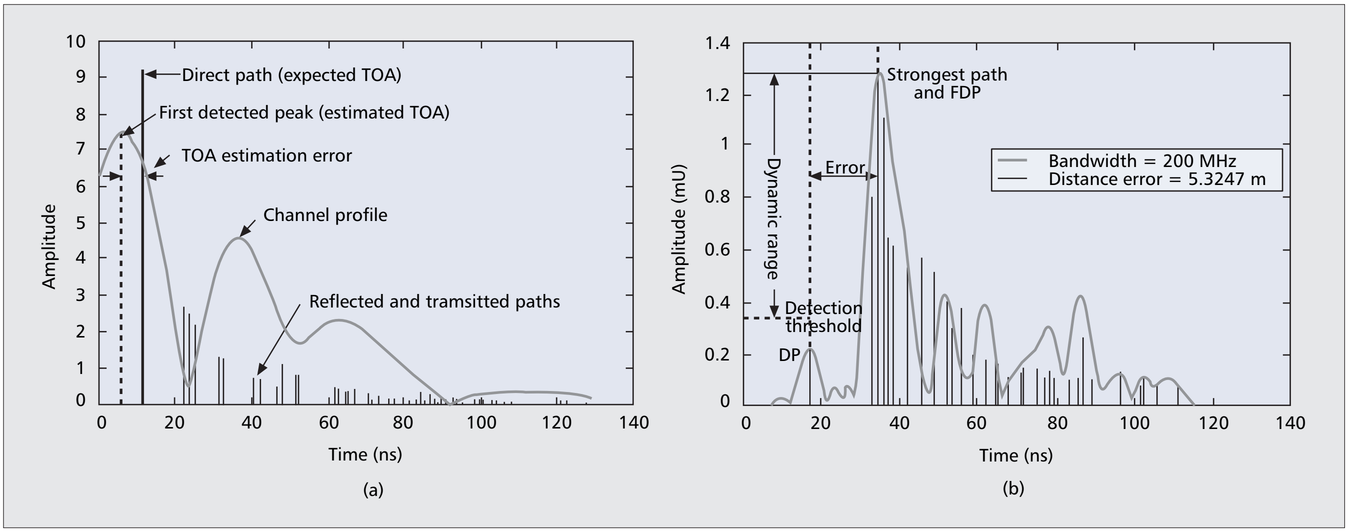


Figure 1. *a) Effects of multipath in the estimation of TOA of the DP; b) distance error in UDP condition.*

receiver, and finding algorithms that can cope with these errors. Results of wideband measurement and modeling in a variety of indoor areas obtained in the past decade have revealed that large ranging errors are caused by severe multipath conditions and frequent absence of direct path in the received signal [1, 7].

Results presented in this article shed light on the root cause of the problem and help in evaluating the potential usefulness of two novel techniques for robust precision indoor geolocation systems. We believe these results can benefit the evolution of the next generation of robust precise indoor geolocation systems. We begin by defining a scenario for dynamic performance evaluation of indoor positioning techniques. We use the results of ray tracing in the dynamic scenario to analyze the cause of undetected direct path (UDP) conditions. Then we introduce two novel techniques for precise localization in the absence of direct path. We use ray tracing results for our analysis because with ray tracing we can extend our results to infinite bandwidth and relate angle of arrival to the multipath components of the channel. Readers interested in the details of our actual measurements can refer to [7].

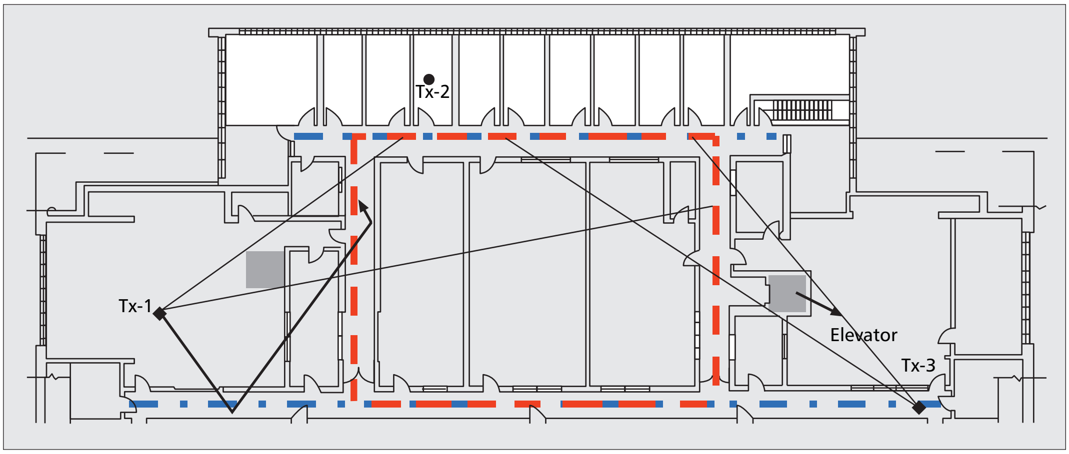
TWO SOURCES FOR RANGING ERROR

In TOA-based localization systems, the TOA of the first detected peak (FDP) of the received signal is used to determine the time of flight, τ, and consequently the distance between a transmitter and a receiver, $d = \tau c$, where c is the speed of light. Figure 1a [3, 7] shows the basic concepts involved in the TOA range measurement using FDP in a typical indoor multipath environment. In this figure the solid vertical lines represent the ideal channel impulse response generated by a ray tracing algorithm for two arbitrary locations in an office area. The direct path (DP) is also the strongest path (SP), and the location of this path is the expected value of the TOA, which can be used for calculation of the exact distance between the transmitter and the receiver. Other paths arriving after a number of reflections and transmissions occur after the DP with lower amplitudes. These paths generated by ray tracing algorithms would have been observed at the receiver if the bandwidth of the system was infinite. In practice bandwidth is limited, and the received signal will be a number of pulses whose amplitudes and arrival times are the same as impulses but having a pulse shape. The addition of all these pulse shapes forms the received signal, shown in Fig. 1, to which we refer as the channel profile.

Ranging Errors Caused by Bandwidth Limitations — In traditional indoor geolocation systems we use the FDP of the channel profile, received above the detection threshold, to estimate the TOA of the DP, and thereby determine the distance between a transmitter and a receiver. In a single path environment the actual expected and estimated DP are the same. However, in multipath environments, as shown in Fig. 1a, when we have other paths close to the DP, the peak of the channel profile is shifted from the expected TOA, resulting in a TOA estimation error. We refer to the ranging error caused by erroneous estimate of the TOA as distance measurement error (DME). As the transmission bandwidth of the system increases, the pulses arriving from different paths become narrower, and the estimate of the TOA by the FDP becomes closer to the expected TOA of the DP, resulting in a smaller DME. Therefore, the first cause of ranging errors in multipath channels is the multipath components in the vicinity of the DP, and we can control these errors by increasing the system bandwidth.

Ranging Errors Caused by UDP Conditions — As we first explained in [1], in obstructed-line-of-sight multipath conditions, when the DP falls below the detection threshold we have a UDP condition. Under these conditions the FDP in the profile is independent of the arrival time of the DP, causing a large random DME. Figure 1b shows an example of the occurrence of a large error due to UDP conditions, taken from the results of ray tracing for a transmitted pulse with a bandwidth of 200 MHz. Since the difference

Unlike the DME caused by multipath components close to the DP, large DME values caused by UDP conditions persist even when we increase the bandwidth to cover UWB frequencies.



■ **Figure 2.** *Dynamic scenario on the third floor of Atwater Kent Laboratory at the Worcester Polytechnic Institute.*

between the strength of the SP and DP is greater than the dynamic range[1] of the receiver, we have a UDP condition resulting in a 5.23 m DME. Unlike DME caused by multipath components close to the DP, large DME values caused by UDP conditions persist even when we increase the bandwidth to cover UWB frequencies. In the next section we show that UDP conditions are not accidental, and they occur frequently in all multipath-rich indoor areas.

TWO CLASSES OF UDP CONDITIONS

Two classes of unavoidable UDP multipath conditions occur in a typical indoor geolocation scenario. The first class of UDP conditions occurs when a large object such as an elevator or a metallic chamber blocks the DP between the transmitter and the receiver. We refer to this first type of UDP condition as shadowed UDP because the huge metallic object shadows the direct connection between the transmitter and the receiver. Under shadowed UDP conditions, the distance between the transmitter and the receiver could be short, and consequently the total received signal power could be large. The second type of UDP condition occurs in areas of low received power in obstructed-line-of-sight environments when, due to the large distance between the transmitter and receiver, the power of the DP falls below the detection threshold but there are still other paths arriving with signal strengths above the threshold level. We refer to this class with low received signal power as the natural UDP condition because it occurs naturally in any indoor area, even in the absence of large metallic objects. In order to discuss these effects in greater depth, we need to define a scenario of operation, as described below.

A DYNAMIC SCENARIO FOR PERFORMANCE ANALYSIS

In this section we introduce a dynamic scenario of operation with defined walking routes in a typical office building so that we can continue our discussions with more quantitative performance analysis. Figure 2 shows our dynamic scenario on the third floor of the Atwater Kent Laboratories at Worcester Polytechnic Institute, where a user walks along different routes in the central part of the building. There are two large metallic objects on the two sides of this floor plan: an elevator on the right and an RF-isolated chamber on the left. These two objects block the signal paths; in particular, they cause shadowed UDP conditions when they are situated between the transmitter and the receiver. Figure 2 shows three walking routes in the building, the upper and lower routes in which the mobile user walks across a straight line from one end to the other end of a corridor, and a loop route in which the mobile user walks loops in the central part of the building. Transmitter 1 (Tx-1) is located in the middle of the large laboratory on the left. For this transmitter, we have substantial shadowed UDP conditions in the upper and left side corridors, but there are no shadowed UDP conditions in the lower and right side corridors. When the mobile takes the central loop route, it observes a shadowed UDP condition approximately 40 percent of the time. With Tx-1, as we trace the mobile along the routes, we can observe different possibilities for occurrence of UDP conditions to analyze the behavior of the large ranging errors and effectiveness of different techniques in mitigating them. In the last part of our discussions, where we discuss cooperative localization techniques, in addition to Tx-1 we also use Tx-2 and Tx-3 for two-dimensional positioning needed to explain these techniques. To carry out the analysis, we use our wideband measurement calibrated ray tracing software reported in [3] to generate channel impulse responses along the routes every 13 cm (the resolution of the graphical user interface).

DME IN THE ABSENCE OF DIRECT PATH

As the first step in our analysis, we take the blue upper and lower routes in Fig. 2 for Tx-1 to demonstrate the behavior of the DME in shadowed and natural UDP conditions, and relate it to other important propagation parameters such as total power, power of the DP, and power of the FDP. Figure 3 shows these three parameters and the resulting DME in the upper and lower routes. The powers of the DP and FDP are the same except when a UDP condition occurs. The

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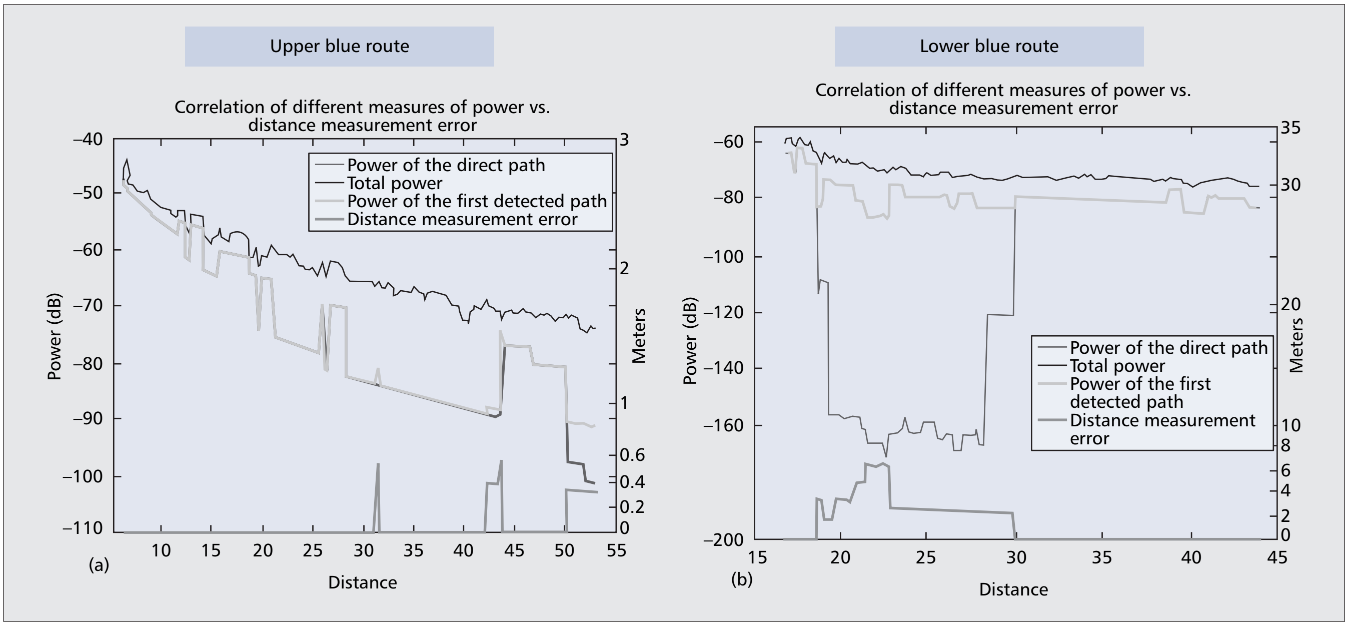
[1] *Dynamic range of a receiver is the range of detectable signal level below the SP.*



■ **Figure 3.** *Total power, FDP power, and DP power for: a) upper route; b) lower route.*

graph on the left representing the lower route does not have any shadowing UDP conditions. There are three short bursts of natural UDP errors with DME values of less than 0.5 m occurring at around the 30, 45, and 50 m markers between the transmitter and the receiver. In these areas the difference between the powers of the DP and FDP is around 10 dB. The graph on the right demonstrates a clear example of shadowed UDP conditions, when the mobile is following the upper route. As the mobile moves along that route, from the distance markers at around 18–30 m, the metallic chamber creates a shadowed UDP condition causing DMEs on the order of several meters and a difference of around several tens of decibels between the DP and the FDP. This analysis demonstrates that during shadowed UDP conditions we have a substantial drop in the power of the DP and large DMEs, while in natural UDP conditions we have a moderate drop in power of the DP and relatively smaller DMEs.

EFFECTS OF BANDWIDTH

As explained earlier, DME is caused by either the limitations in the bandwidth of the system or the occurrence of UDP conditions. We consider our loop scenario and Tx-1, for which the occurrence of UDP conditions is around 40 percent of the locations, to demonstrate the effects of bandwidth on overall performance. Figure 4 shows the cumulative distributed function (CDF) of the DME in our loop scenario for the Tx-1 and a variety of bandwidths. The solid line is associated with the direct results of ray tracing in which each path is represented by an impulse with infinite bandwidth. In around 60 percent of the locations, on the lower parts of the loop we detect the direct path, and with infinite bandwidth, we estimate the exact distance between the transmitter and the receiver with zero DME. For the remaining 40 percent of the locations the RF isolation chamber blocks the direct path causing positive values of up to 7 m for the DME due to erroneous detection of the FDP rather than the DP in the channel impulse response. As we gradually decrease the bandwidth to 300, 200, and 100 MHz in Fig. 4a, the larger DME values due to the bandwidth effects appear in the CDF of the plots. Since DME due to bandwidth limitations can shift the FDP of the channel profile in either direction, we can now observe negative DMEs as well. Reduction in the bandwidth spreads the range of the errors. For example, with 100 MHz bandwidth we have errors between –5 and 10 m.

Figure 4b uses narrower bandwidths up to 10 MHz for which the DME is spread between –30 and 40 m in a loop in which the maximum distance between the transmitter and the receiver is less than 40 m. Therefore, bandwidths on the order of 10 MHz used in global postioning systems (GPS) are not sufficient, and we need bandwidths on the order of several hundred megahertz to provide reasonable protection against the extensive multipath in indoor areas. For example, for 200 MHz bandwidth, the range of DME is on the order of –3 to +7 m, fairly comparable to UDP errors of up to 7 m observed with infinite bandwidth. To reduce the bandwidth requirements below these values, one may consider using super-resolution algorithms for post processing, which is described in [8, 9]. However, to reduce DME below those observed in UDP areas with infinite bandwidth, we need fundamentally different approaches, which we examine in the following section.

PRECISE LOCALIZATION IN THE ABSENCE OF DP

The sudden and random occurrence of UDP conditions may resemble sudden hits of signal fading in radio communications. Therefore, a seemingly reasonable approach to mitigating the problem is

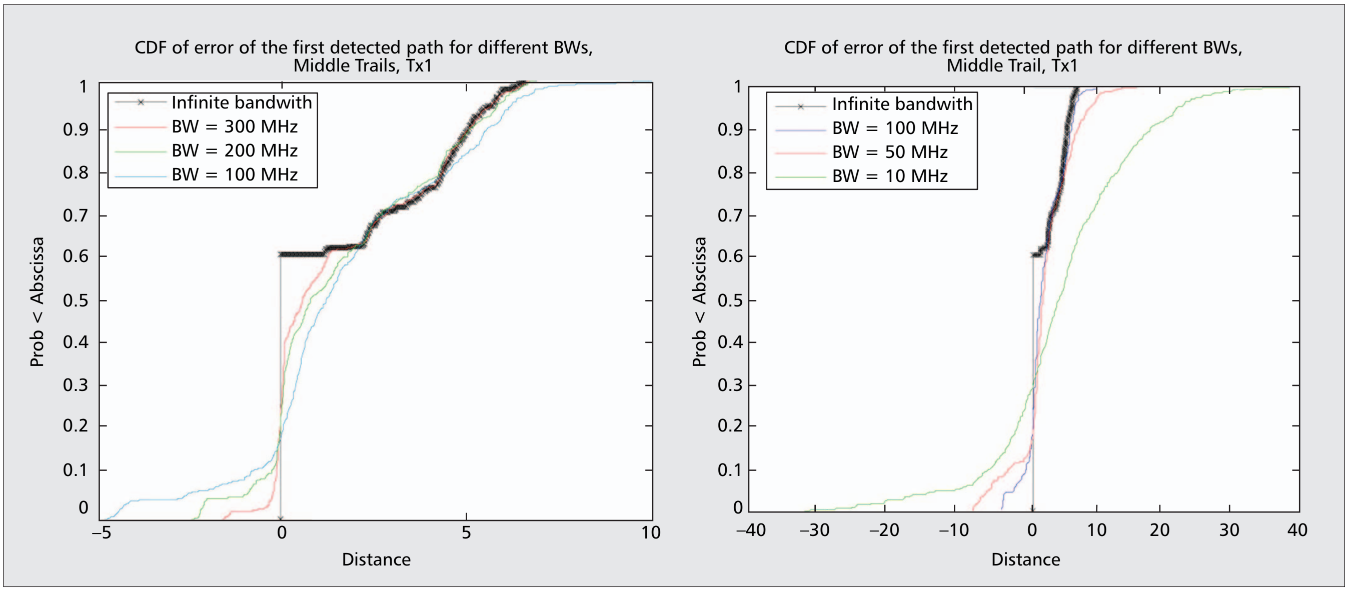


Figure 4. *CDF of error for FDP for a) higher bandwidths; b) lower bandwidths.*

to employ well-known diversity techniques. To improve the performance of a radio modem in fading we can replicate the signal in multiple frequency channels to provide frequency diversity, apply a variety of coding techniques, simply repeat the signal multiple times to provide time diversity, or use multiple antennas to provide space diversity. Since these techniques have been very effective, widely utilized, and are analytically sophisticated, a rich literature has gradually evolved around them in the past 50 years. The latest innovative research in this field has evolved into the introduction of orthogonal frequency-division multiplexing (OFDM) modulation, multiple-input multiple-output (MIMO) systems, and space-time coding techniques [3]. If we ignore the complexity of the behavior of indoor radio propagation and the fact that the models developed for indoor propagation characteristics for telecommunication applications are not useful for indoor geolocation, as first described in [1], using diversity techniques may appear promising. In fact, the lack of understanding of the complexities of indoor radio propagation has been the main source of failure for precise indoor geolocation projects over the past decade. In principle, when the direct path is shadowed, none of the traditional diversity techniques are effective for precise indoor geolocation.

As an example, consider the traditional frequency diversity technique used in frequency selective multipath fading on indoor radio channels. In telecommunications applications the basic principle is that rather than transmitting all the information using one wideband channel, we can send several streams of lower-rate data over multiple narrowband subchannels. If one of the subchannels is hit by frequency selective fading, we can still use other subchannels to achieve reliable communications. This basic principle is very effective in telecommunications applications and is applied in OFDM, which is the technology of choice for wideband data communications in wireless LANs (WLANs), WPANs, and WiMAX. If we apply the same basic concept to indoor geolocation in the absence of direct path, rather than using the TOA of the FDP from a single wideband channel, we can use the TOAs of the FDP obtained from multiple subchannels to reduce the DME. However, in the absence of direct path, when the TOA estimate in one channel is not reliable, it is also unreliable for other subchannels. Therefore, frequency diversity techniques are not capable of providing significant improvements to the performance in UDP conditions.

After nearly a decade of research, since we first analyzed the effects of multipath on the accuracy of the indoor localization systems [1], today our understanding of this important and complicated problem is that traditional radio communication techniques such as frequency diversity, time diversity, and space diversity using MIMO techniques are not effective in mitigating large ranging errors resulting from the absence of direct path. Two promising approaches to precise indoor localization in the absence of direct path are localization exploiting nondirect paths and cooperative localization. Although these approaches to algorithm development are intuitively sound, the degree of their effectiveness and their implementation details in a realistic indoor environment are subjects for future research.

LOCALIZATION EXPLOITING NONDIRECT PATHS

Figure 5 illustrates the basic principle underlying the relationship between the TOA of the direct path and a path reflected from a wall for a simple two-path scenario. As the mobile receiver moves along the *x*-axis, the change in distance in that direction is related to the length of the DP by $dx \cos \alpha = dl_{DP}$. As the geometry of Fig. 5 shows, for the reflected path we also have $dx \cos \beta = dl_{P_n}$. Therefore, we can calculate the change in the length of the direct path from the change in the reflected path using

$$dl_{DP} = dl_{P_n}\frac{\cos\alpha}{\cos\beta} \quad \text{or} \quad d(TOA_{P_n}) = d(TOA_{P_n})\frac{\cos\alpha}{\cos\beta}. \qquad (1)$$

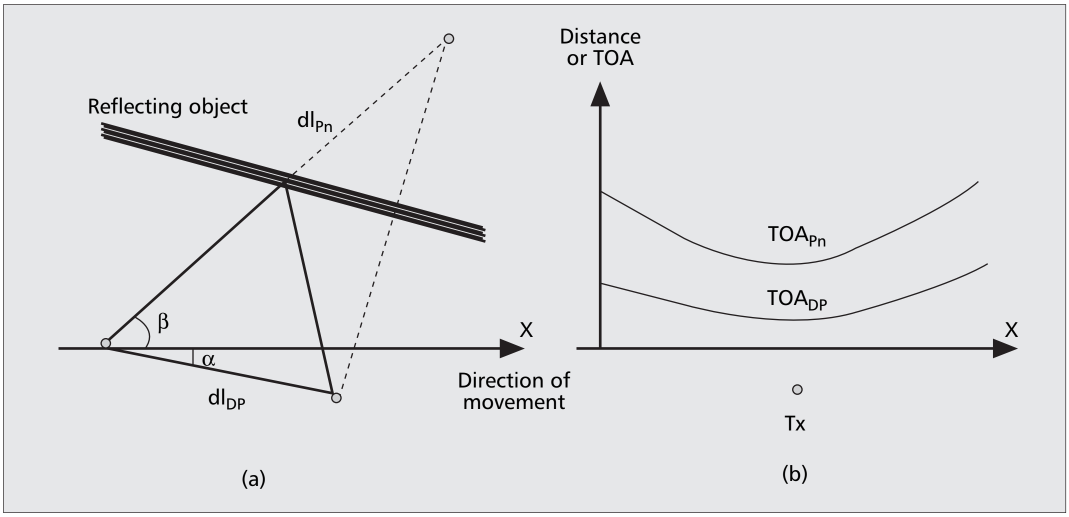


Figure 5. *a) Basic two-path reflection environment; b) relation between the TOA of paths.*

In order to use a path other than the DP for tracking the location, we should be able to identify that path among all other paths, and the number of reflections for that path should remain the same in the region of interest.

In other words, knowing the angle, β, between the arriving path and direction of movement, and the angle, α, between the direction of movement and the DP, we can estimate the changes in the TOA of the DP from changes in the TOA of the reflected path. This basic principle can be extended to paths reflected from many objects and to the three-dimensional case as well. This general treatment is available in [10–12].

In indoor geolocation applications we can think of applying this principle to locating a mobile in UDP areas in the absence of DP. Knowing the previous location of the transmitter and the direction of movements, we can always calculate α even in the absence of the DP. If we can find a way to measure β, using values of α and β in Eq. 1 we can track the location as the mobile receiver moves along in a UDP environment.

Practical Challenges for Indoor Geolocation Applications — In order to use a path other than the DP for tracking the location, we should be able to identify that path among all other paths, and the number of reflections for that path should remain the same in the region of interest. In the simple two-path model shown in Fig. 5, the second path consistently reflects from one wall as we move along the region; hence, we can identify that path easily because it is the only path other than the DP. Since both conditions hold for the second path, the behavior of the TOA of that path, shown in Fig. 5b, is smooth, and we can use it for tracing the DP. In realistic indoor scenarios, in the absence of DP, we have numerous other paths to use, and the simplest paths to track are the FDP and SP. To demonstrate the detailed behavior of these two paths in a practical situation, once again we use our scenario.

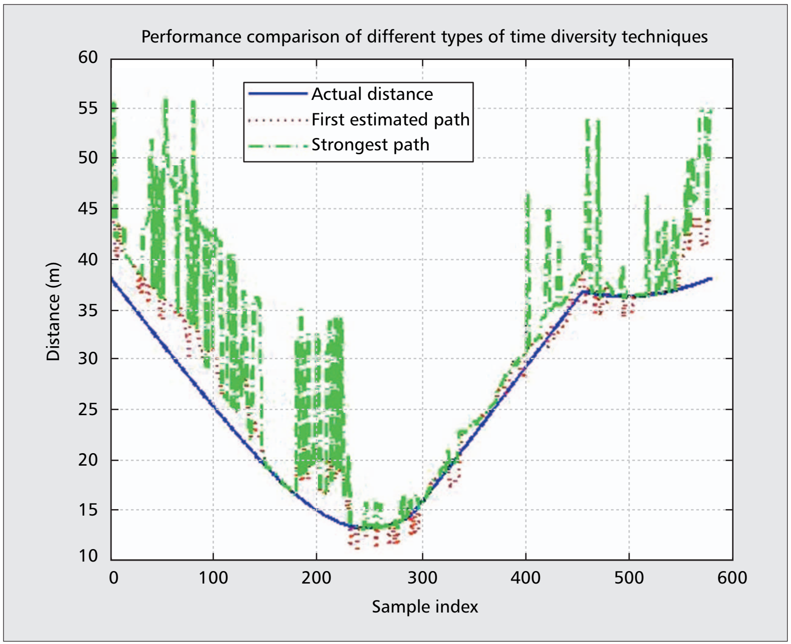
Figure 6 shows the behavior of the distances calculated from the TOA of the FDP and the SP for a system with 200 MHz bandwidth, and a comparison with the actual distance between Tx-1 and the receiver when the receiver moves across the loop in our example scenario shown in Fig. 2. Both the SP and FDP have inconsistent behavior in the UDP region of interest. This inconsistent behavior is caused by changes in the path index of these paths. In other words, if we associate a path number or index with a path associated with a specific reflection scenario from given walls, as we move along in a region, the path index or reflection scenario for the FDP or SP changes. Each of these changes causes a jump in the behavior of the TOA of the path, thus impairing the smoothness needed for our estimation process.

AOA and Precise Ranging — With regard to channel behavior, we need to look into the principles underlying this behavior to learn how to remedy the situation. The basic problem is path indexing changes, and the rate of path indexing exchange is a function of number of paths in the impulse response. The number of paths can be reduced by restricting the angle of arrival (AOA) of the received signal using a sectored antenna. Using sectored antennas to restrict the AOA provides two benefits:

- It reduces the number of multipath components and hence reduces the path index crossing rate, facilitating improved tracking of specific paths in the channel profile.
- It allows a means for estimating the angle of the arriving path needed for Eq. 1.

To further clarify the benefits of this technique, we resort again to our loop route scenario to explain the behavior of the SP in the channel impulse response in a receiver using a sectored antenna with a variety of aperture angles.

To begin we examine a sample location on the loop route and use the ray tracing software to generate the impulse response of the channel for different aperture angles to observe how the number of multipath components in a UDP region relates to the aperture angle. Consider the location pointed to by an arrow on the left side of our loop route shown in Fig. 2. The DP between Tx-1 and this location is blocked by the metallic chamber, and the SP is a path arriving after two reflections. The ray tracing generated impulse response of the channel at this location has 590 arriving paths with no restrictions on AOA. With a 45° aperture we have 91 paths, and with 5° the number of paths decreases to 12. As the aperture angle becomes narrower, the



■ **Figure 6.** *Behavior of the distances calculated from the FDP and SP vs. actual distance.*

number of paths reduces significantly, allowing better tracking of a desirable path.

Figure 7 shows the ideal behavior of different paths without bandwidth considerations as a receiver moves along the left segment of the rectangular route. The blue line shows the actual distance, and the blue line with star marker shows the behavior of the FDP, which in this case is also the SP. The receiver starts in a DDP condition, then moves to a UDP region, and then returns to another DDP area. In the DDP regions the DP, FDP, and SP are the same, and the range estimate is accurate and consistent (steady). In the UDP region the FDP, which is also the SP, remains steady for short periods, but due to the path index changes of the FDP it cannot maintain its steadiness and experiences about 15 transitions of the path index or reflection scenario for the FDP. This high rate of transitions is due to the large number of multipath components, and we can reduce these components by using sectored antennas to limit the AOA of the paths.

Figure 7 also shows the behavior of the SP in three neighboring 5° sectors along the UDP region of the left side corridor in Fig. 2. These are three of the 72 ideal 5° sectors assumed in this example. The SP of the entire profile, shown with two reflections in Fig. 2, is first in sector 61, and then moves to sectors 62 and 63. As the SP moves among these sectors, it has a steady behavior with no change in path index, which we can use for the detection of the TOA of the DP.

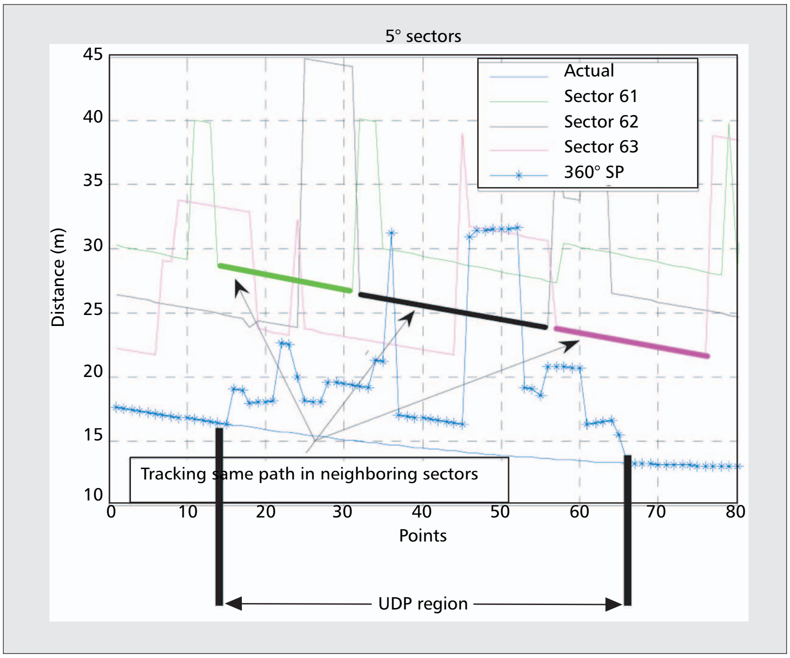
The discussion above shows the potential for the implementation of ranging using nondirect paths with an ideal sectored antenna with 5° aperture angle for each sector and a simple algorithm that traces the SP as it moves from one sector to the next neighboring sector. Development of more practical algorithms to implement this concept with finite bandwidth and realistic antennas will require significant additional research.

COOPERATIVE PRECISE LOCALIZATION

In two-dimensional localization we need at least three links or connections to reference terminals with known locations. These links may have different qualities of estimate for the distance between the reference and target terminals, depending on the availability of direct path in the channel. In cooperative precise localization in multipath-rich environments, we simply avoid ranging estimates reported from the links with UDP conditions. In other words, the redundant information provided by the additional reference points is used to reduce the localization error. This situation is common in ad hoc and sensor networks where we have a fixed infrastructure of known reference points for positioning and a number of mobile users in the area. When we want to locate a mobile terminal, in addition to the distances from the respective fixed reference points, we can also use the relative distances from other mobile users. We refer to this approach as cooperative localization since the localization is conducted through a cooperative method. A similar approach is also used for general localization in sensor and ad hoc networks when we have a limited number of dispersed references and a number of ad hoc sensor terminals with less than an adequate number of connections to reference points [13, 14]. For general localization we only need the whereabouts of the terminals, and the literature in that field does not address the large error caused by UDP conditions. The concept introduced in this section uses the redundancy of the links embedded in the sensor and ad hoc network environments to achieve precise indoor localization. To clarify our new concept we resort again to an example using our scenario.

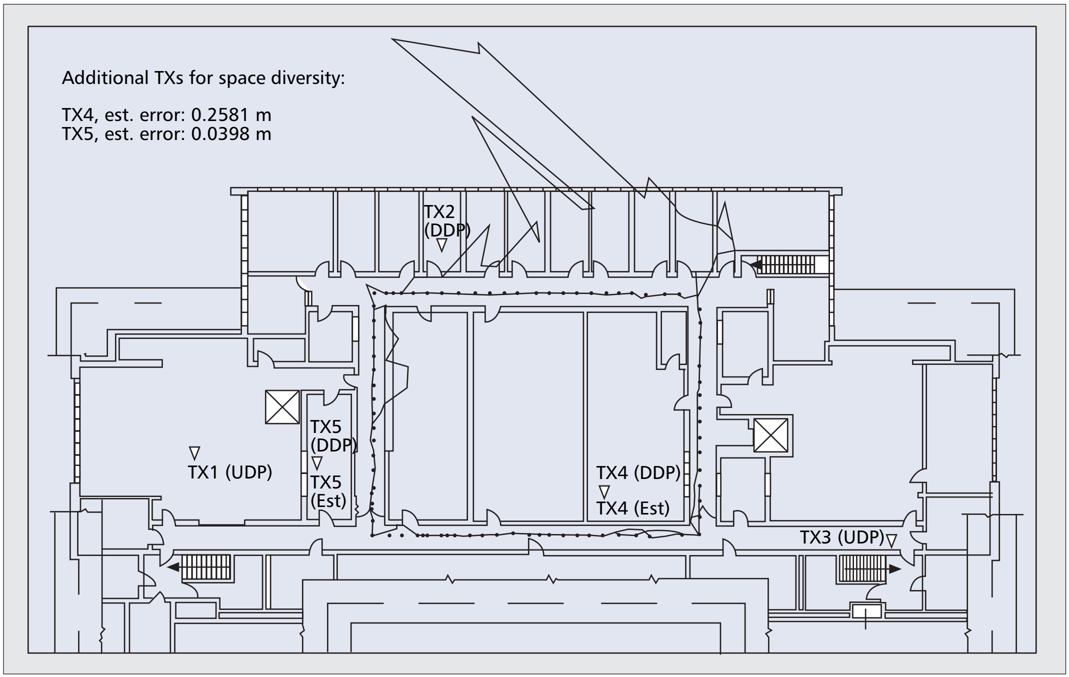
Figure 8 shows a positioning scenario with three reference transmitters in our selected office building and the loop route scenario. Tx-1, located in a large laboratory on the left side of the building, has UDP conditions caused by the RF isolation chamber in 40 percent of locations around the loop; Tx-2, located in the small office in the upper part of the building layout, covers the entire loop without any UDP location; and Tx-3, located in the lower corridor, has around 50 percent UDP conditions around the loop caused by the elevator. The red line in Fig. 8 shows the results of location estimation using the traditional least square algorithm [3] with the three known reference transmitters along the loop. Whenever a direct path is present (e.g., in the lower and righthand routes), the DME is small. As we have one or two UDP conditions for our three links to the references (e.g., in the upper route), the DME is substantially large. This observation suggests that whenever a direct path is available for all links, we can achieve precise localization, but as soon as one of the links loses the direct path, we have large localization errors. In other words, if we avoid UDP conditions, we can achieve precise positioning. Therefore, if we have more than the minimum number of references, assuming we can detect the UDP conditions, we can avoid links with UDP and achieve precise localization.

To demonstrate the effectiveness of this approach, we consider an example where we have two other users, Tx-4 and Tx-5, which are located in good positions, where each has three direct path connections to the main reference transmitters. As shown in Fig. 8, when we use the three main reference transmitters to estimate the location of Tx-4 and Tx-5, we have very good estimated locations for them. In an ad hoc sensor environment we can assume that our target receiver moving along the loop route can also measure its distances from Tx-4 and Tx-5. In this particular example, as shown in the figure, these ranging estimates are also very accurate because they are based on the availability of the direct path. The dotted line in Fig. 8 shows the estimate of location for the mobile terminal as it moves along the loop when it uses the estimated locations of Tx-4 and Tx-5 and the actual location of Tx-2 to locate itself with the traditional least square algorithm. As shown in Fig 8, our estimates are now substantially more accurate. The drastic improvement in the accuracy of localization is a result of avoiding UDP conditions and taking advantage of the redundancy of the ad hoc sensor networks to achieve precise cooperative localization.



■ **Figure 7.** *Effectiveness of AOA in the UDP region.*

In the above example we show the potential advantage of using redundancy in sensor and ad hoc networks to achieve precise cooperative positioning. In practice, we need to develop algorithms for implementation of this concept. These algorithms need the intelligence to discover the quality of ranging estimates and possibly occurrence of UDP conditions to use them for positioning. The algorithms for general cooperative localization, first suggested in [13] and later discussed in the followup literature [6, 14], are not applicable to our approach. We need new algorithms to address specific methods to handle the behavior of DME errors in the absence of direct path, which is reported in [7]. We have to find techniques for relating a quality of estimate to each ranging and positioning estimate in order to develop precise cooperative localization algorithms for sensor and ad hoc networks. These algorithms should take advantage of redundancy to avoid unreliable reference sources and achieve robust precise localization. A preliminary algorithm using the channel behavior to implement a practical solution for precise cooperative localization is available in [15]. More research in this area is needed for the design of algorithms that take different radio propagation conditions into account.



■ **Figure 8.** *Demonstration of space diversity on the third floor of Atwater Kent Laboratory.*

CONCLUSIONS

After nearly a decade of major research initiatives by government and industry, precise localization in multipath-rich indoor areas remains as a challenge facing the research community. Today our understanding of this important and complicated problem is that the frequent absence of direct path in indoor areas is the cause of large ranging errors that cannot be resolved by using ultra wideband signals or with traditional techniques such as frequency diversity, time diversity, or space diversity using MIMO techniques. Two promising approaches to precise indoor localization in the absence of direct path are localization exploiting nondirect paths and cooperative localization. Although these approaches to algorithm development are intuitively sound, the degree of their effectiveness and their implementation details in a realistic indoor environment require further research.

Two promising approaches to precise indoor localization in the absence of direct path are localization exploiting non direct paths, and cooperative localization. Although these approaches are intuitively sound, the degree of their effectiveness and their implementation details in a realistic indoor environment require further research.

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