Error Mechanisms in Indoor Positioning Systems without Support from GNSS

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ABSTRACT

There exist various applications for indoor positioning among which indoor positioning and tracking in urban environments has gained significant attention. Some user communities, like fire fighters, ideally require indoor accuracy of less than one meter, with accuracies of less than six meters acceptable by some other user communities. Achieving this level of accuracy requires a detailed profiling of error sources so that they can be better understood and indoor positioning accuracy in presence of these errors can be further improved upon. Some well-known error sources like multipath, NLOS, oscillator drift, Dilution of Precision and others have been studied and can be found in the literature. A less well-known error source that can substantially affect indoor positioning accuracy are the effects of the dielectric properties of building materials on propagation delay.

Various RF and non-RF based prototypes that claim to be suitable for indoor positioning can be found in the literature. Most of the existing literature discusses algorithms and summarizes the positioning results that were achieved during field tests, using a prototype system or even more commonly simulations. Little of this existing literature provides a breakdown of the total navigation system errors observed with the objective of analyzing the contribution of each of error source independently.

The paper will first provide a brief overview of the precision personnel locator system developed at the Worcester Polytechnic Institute. The field tests and observed indoor positioning results using this RF prototype will then be summarized and used to provide a baseline for establishing a system error budget. The total observed error will be broken down and a detailed analysis of each of the error sources will be presented based on actual measured data in a variety of indoor environments. This will lead to a better understanding of how each error source effects indoor positioning accuracy. Each of the error sources can then be independently optimized to minimize the observed errors. Specifically, the interplay between the dielectric properties and multipath profiles will be highlighted. This paper will conclude by presenting an error budget which can be used as a practical lower bound when designing precise indoor positioning systems.

INTRODUCTION

Indoor positioning and tracking without the support of GNSS is one of the challenging problems being faced today which has numerous applications, especially in the field of emergency services like law enforcement and fire and rescue operations. Figure 1 provides an overview of a RF-based precise positioning system being developed at Worcester Polytechnic Institute. The goal of this system is to provide a robust real-time indoor location system that does not require any pre-existing infrastructure. As shown in Figure 1, the fire trucks and fire fighters reporting at the scene of an incident will each be fitted with hardware components which, in aggregate, form the envisioned location system. The fire fighters carry a transmitter which continuously transmits a radio signal. The radio signal used is a MultiCarrier-UltraWideband (MC-UWB) signal structure shown in Figure 2. Such a MC-UWB signal is much easier to adapt to existing spectral assignments [1, 2] than other proposed signals [3, 4]. The MC-UWB signal is then received by multiple receivers mounted on the emergency vehicles. The signals received at the vehicles are then used to calculate the relative positions of fire fighters in and around the building using a TDOA-based position estimation algorithm.

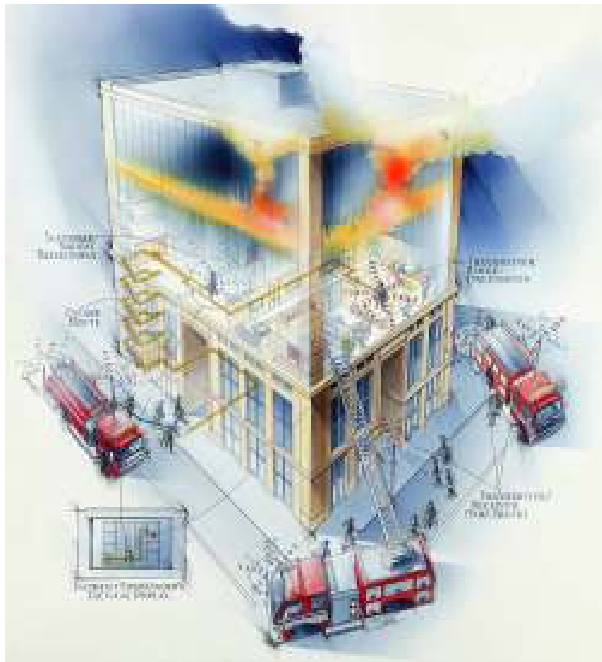

Figure 1: Precise Positioning System Application Overview

The position information for each fire fighter is then sent to a central command and control display which provides the incident commander situation awareness information on the fire ground. The positioning accuracy requirements for such an indoor positioning system are high, with better than 3m being ideal, and 3m to 6m being acceptable. In addition to providing position information, it is also desirable to provide health and vital sign information along with environment sensing and temperature monitoring.

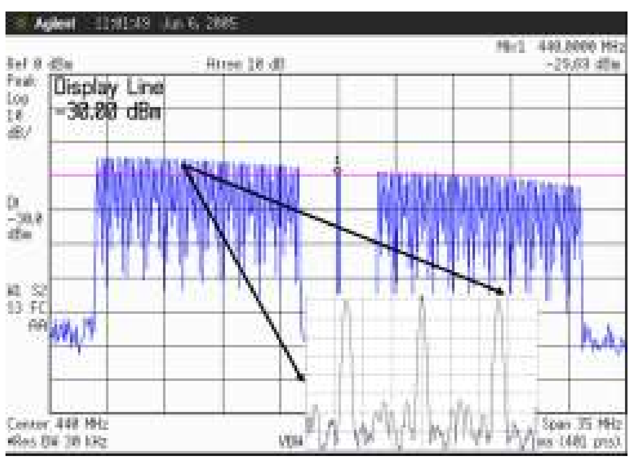

Figure 2: MC-UWB Signal Structure

RF PROTOTYPE TEST SETUP

The system architecture of the developed prototype system is shown in Figure 3. The prototype system consists of a single transmitter and five receivers, resulting in four TDOA equations. The MC-UWB baseband transmit signal is generated using an FPGA. It undergoes digital to analog conversion and is then upconverted to the required RF frequency. The receiver downconverts and then digitizes the signal. The FPGA at all the five receivers contains the buffered data that is then transferred to the PC for further signal processing. The TDOA-based algorithms implemented in the PC calculate a position estimate for each transmitter.

The multicarrier signal structure consists of multiple sinusoids which makes the RF design of such a positioning system difficult compared to conventional single carrier or narrowband RF system designs. The prototype system was developed to operate over 148MHz centered at 625MHz (550MHz to 698MHz). Thus, the RF fractional bandwidth is 25% and designing the RF transmitter and receiver for such large fractional bandwidths becomes challenging as the RF components are stressed using multicarrier signal in a way not anticipated by the designers.

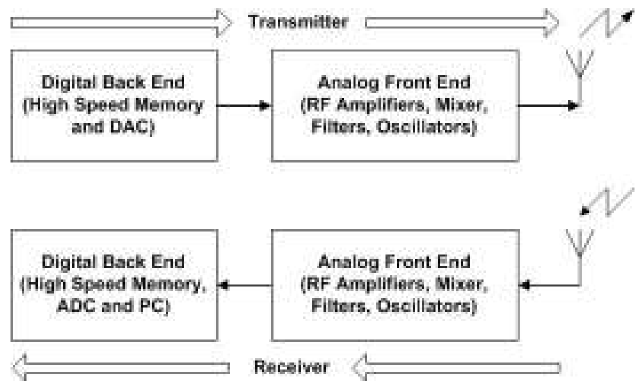

Figure 3: Overview of the RF Prototype System Architecture

The 148MHz bandwidth transmitter consists of a Low Pass Filter (LPF), Up Conversion Mixer, Gain Block, Power Amplifier (PA) and Band Pass Filter (BPF). The Low Pass Filter is realized by a 7th order elliptical LC filter, providing the sharp roll off required to eliminate the DAC aliasing signal. It is desired to use a LPF based on an LC design, as it has low insertion loss, high power handling and flexible design. A high performance passive mixer is used to implement the upconverter. A mixer with wide bandwidth, very low intermodulation distortion, and good LO-RF rejection is used. The mixer used in the transmitter is suitable for high intercept point applications.

An onboard RF phase locked loop frequency synthesizer is used to generate the required mixer local oscillator. The crystal oscillator used in the PLL implementation provides a 10 MHz reference frequency, and a phase noise of -143dBc/Hz at 1MHz offset from the required carrier. The Band Pass Filter is a 7-section Chebychev LC filter which is hand tuned and optimized over the 148MHz RF spectrum. Multiple stages of highly linear amplifiers are tuned to provide a total transmitter output power of 10dBm. The custom made RF transmitter PCB is shown in Figure 4. The transmitter was optimized to achieve magnitude flatness of approximately +/-1dB across most of the 550MHz to 698MHz spectrum.

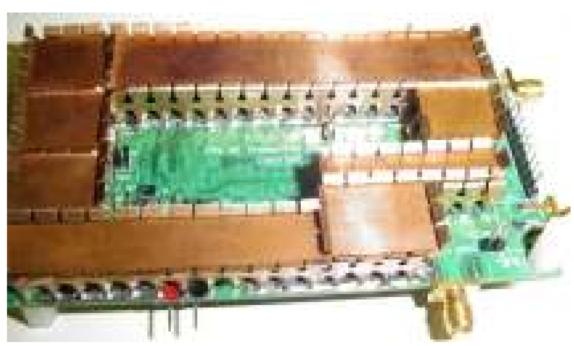

Figure 4 RF Transmitter Front End PCB

The 148MHz bandwidth receiver consists of four antenna input ports, Band Pass Filter (BPF), Low Noise Amplifier (LNA), Down Conversion Mixer, Variable Gain Control (VGC), and Low Pass Filter. The band pass and low pass filters are a custom-made 7-section LC filter configuration. The selection of the LNA is crucial as the noise figure of the LNA sets the noise figure of the receiver. The LNA chosen has a high gain of 20dB and a low noise figure of 1.6dB. The wideband mixer that follows the LNA is a high performance active mixer.

Similar to the transmitter, the PLL frequency synthesizer provides the mixer with the required local oscillator signal. The output of the mixer drives a digitally controlled variable gain amplifier. The four antenna input ports support spatial diversity as four antennas can be connected to the receiver. Similar to the transmitter PCB shown in Figure 4, a custom receiver PCB was also designed. The receiver was also optimized to achieve a magnitude flatness of approximately +/-1dB across the 550MHz to 698MHz spectrum.

NLOS FIELD TEST SETUP AND POSITIONING RESULTS

The 148MHz bandwidth system discussed in the previous section was used to perform NLOS indoor tests. The transmitted multicarrier signal consisting of 51 subcarriers, spans from 550MHz to 698MHz and the downconverted signal spans from 30MHz to 178MHz. Field tests were performed at various indoor locations, one of which is shown below in Figure 5, which is approximately a 20m x 20m brick walled building. The test setup uses a single transmitter inside this building with five receivers placed outside with their directional antennas looking inside the building through the brick walls. Each of the five receivers has four antenna input ports, making the system capable of deploying up to 20 antennas. For the test venue shown in Figure 5 a total of 16 receiving antennas were carefully placed around the three sides of the brick building, to optimize the geometry.

Figure 5 Indoor Positioning Field Test Venue

The transmitter was moved inside the brick walled building at eight different locations and the position estimate at each of the eight transmitter locations was calculated. The average error from all the eight locations was 2.84m, with the maximum error being as high as 6.6m. The position estimation results are calculated using super-resolution algorithms [5] to separate the direct path from the multipath. The multicarrier signal offers frequency diversity; multiple antennas offer spatial diversity and were deployed to optimize the receiver geometry. Also note that the operating area of the testing venue was such that the signal received at all the antennas maintained a high SNR. Implementing all of the above optimization techniques resulted in improving the positioning errors and bringing them in the range of 3m to 6m. It is desired to further improve the error and bring it as close as possible to 1m, which is ideal for the fire fighter user community. Thus, it becomes important to identify the remaining sources of errors that could be causing the observed 3m to 6m errors in position estimates.

ERROR SOURCES

After extensive simulations, bench tests and field tests the error sources and their contribution in field tests discussed above were determined and are tabulated in Table 1. The errors affecting the accuracy of location estimates can be broadly divided into three groups:errors due to the radio hardware, errors in theestimation algorithm and errors due to the channel impairments. This classification of error sources is illustrated in Figure 6. Radio hardware error sources include factors such as sampling clock offsets and drifts as well as local oscillator offsets and drifts. The performance of the location estimation algorithm depends upon many factors such as receiver geometry and number of blocks used to compute the estimates [2]. The most commonly discussed channel impairment includes effects of path loss, NLOS components and multipath. However another prominent source of error which has often been neglected is that due to the dielectric properties of the materials used to construct the building itself.

Discrepancies in the transmitter and receiver sampling clocks result in degrading the positioning estimate. Using a sampling clock crystal of 10ppm or better minimized this error to less than 0.003m. Similarly, the local oscillator frequency shift and drift results in error and using the crystal that was 2.5ppm or better, resulted in contributing less than 0.003m error. Receiver geometry and dilution of precision (DOP) plays an important role to minimize errors in TDOA based systems and should be optimized. For example, having receivers only on three sides of the brick building and not all four sides contributes to errors up to 0.3m. Antenna polarization, radiation pattern and antenna type also affect the position estimate to up to 0.3m. Directional antennas are desirable at the receivers, which along with optimum receiver geometry will result in less error.

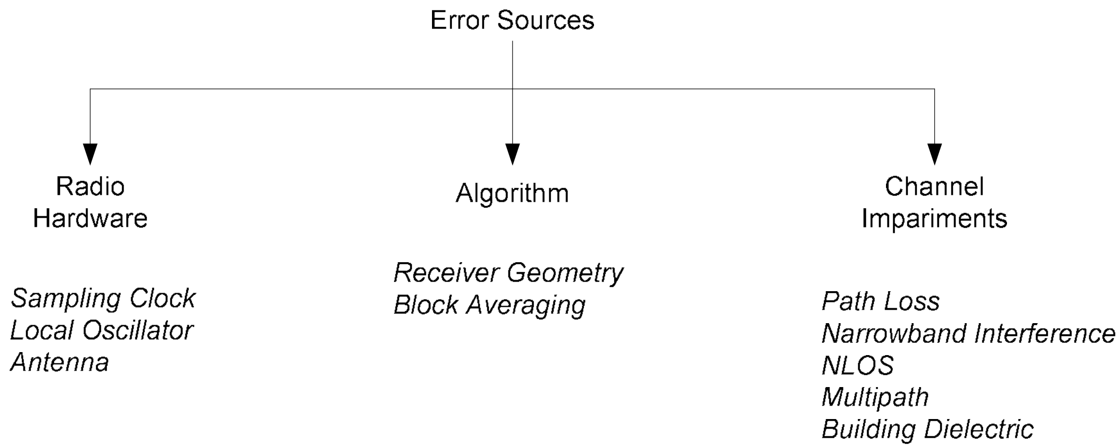

Figure 6 Types of Error Sources.

Table 1 Error Budget

Error Source	**Error (meter)**	**Design Constraints / Comments**
Sampling CLK Shift	0.003	< 10 ppm: Sampling CLK frequency error
Sampling CLK Drift	0.003	< 10 ppm: Sampling CLK frequency error
Local Oscillator Shift	0.010	< 2.5 ppm: Local oscillator frequency error
Local Oscillator Drift	0.010	< 2.5 ppm: Local oscillator frequency error
Receiver Geometry	0.30	Optimum receiver geometry Very important
Antenna Type	0.30	Need to use directional antennas at receivers
Software Processing	0.10	Optimum selection of the useful spectrum
Path Loss / Shadow Fading	0.10	AGC implementation at the transmitter and receiver
Narrowband Interference	0.30	Optimum selection of the useful spectrum
NLOS	0.50	Better geometry, antenna, transmit power required
Multipath	0.50	Need for channel models specific to indoor positioning
Building Dielectric Properties	0.50	Need to characterize delays induced by various building materials
Total Error	**2.626**	

High range of variable gain control implementation both at the transmitter and at the receiver could be useful in combating severe path loss and shadow fading in NLOS indoor conditions. Narrowband interference from in-band TV stations can add 0.3m error in the position estimate. Signal processing algorithms that could optimally select only useful spectrum eliminating the narrowband interference portion of the spectrum can help reduce this error. It is well known that multipath and NLOS are the two major contributors for indoor positioning with each adding error of 0.5m or more. In addition to the above mentioned error sources, there is one error source that is less well known and can result in adding errors of 2m or more. The building material dielectric properties result in adding delay to the transmitted signal as the RF wave inside the material is going to be slower than the propagation of the RF wave in free space. Accounting for these identified sources of error results in an RSS error of about 2.62 m. Contributions of individual error sources in the cumulative error budget are shown in Figure 7. The materials used in the construction of a building do have an effect on position estimation inside the building. The most common building materials are concrete, bricks and wood. Simulations [6] were performed to better understand the expected errors introduced by the dielectric properties of the building materials used.

Consider a NLOS, multipath free example of positioning inside a brick building as shown in Figure 8. As shown in Figure 8, the four receivers are outside the building and are equidistant from the transmitter located inside the building. The three sides of the building consist of brick walls and one side consists of a wooden wall. The transmitter inside the building transmits the signal and for three sides, this signal penetrates through two brick walls and is received by receivers outside. The transmitter position was estimated for this NLOS, multipath-free simulation setup. The simulation results do not consider the errors due to SNR degradation or due to multipath. The simulated position estimation error for the example depicted in Figure 8 was 0.923m.

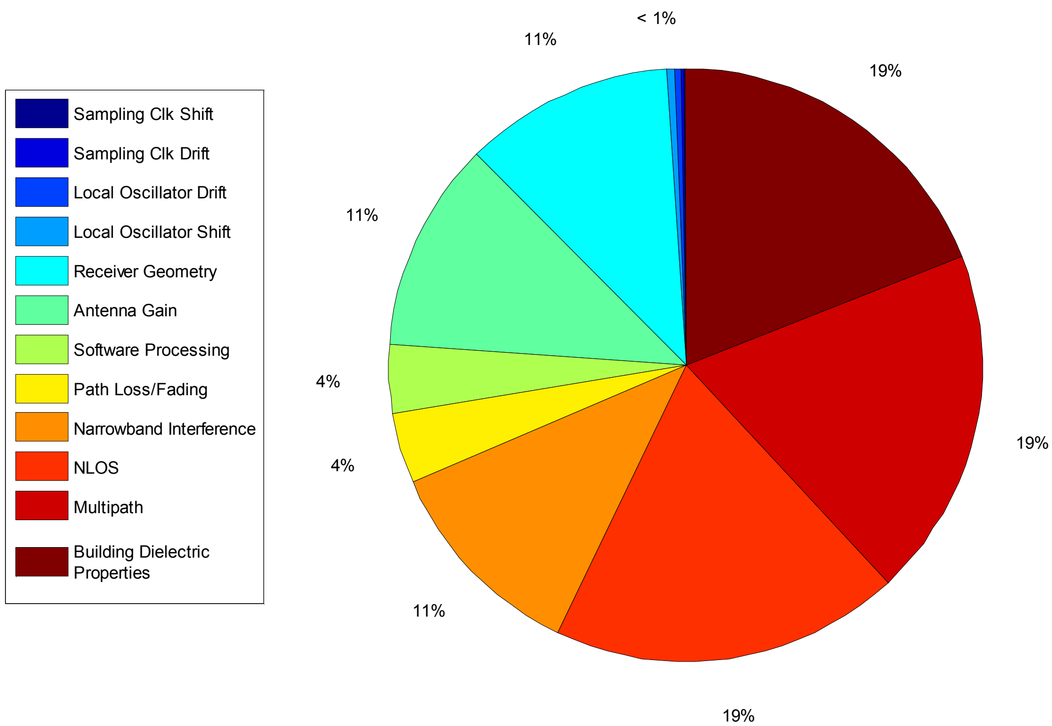

Figure 7 Contributions of Error Sources.

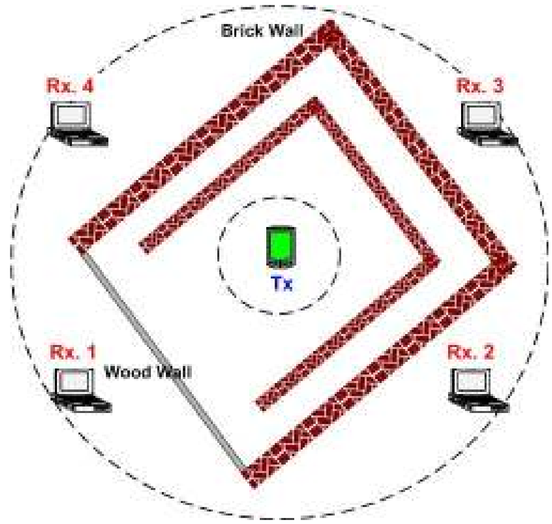

Figure 8 Indoor Positioning in Residential Area

This error of 0.932m is purely due to the delay introduced in the transmitted signal inside the brick walls due to different relative dielectric constant as compared to that in free space. In the simulations, the dielectric constant for brick wall was set to 4.5 and that for the wooden wall was set to 3. The dielectric constants of these building materials are frequency and weather dependent. For example depending on the type of wood, its dielectric will vary from 2 to 5 and depending on the carrier frequency of the transmitted signal, the dielectric for concrete varies from 26 to 10 over 50MHz to 1GHz [7]. For the same transmitter and receiver positions, the simulations were repeated to include effects of few more brick walls as shown in Figure 9, similar to what one would find in a typical office building. The resulting error was 3.48m which is again only due to the effect of signal being delayed by the brick walls, causing errors in the TDOA estimates.

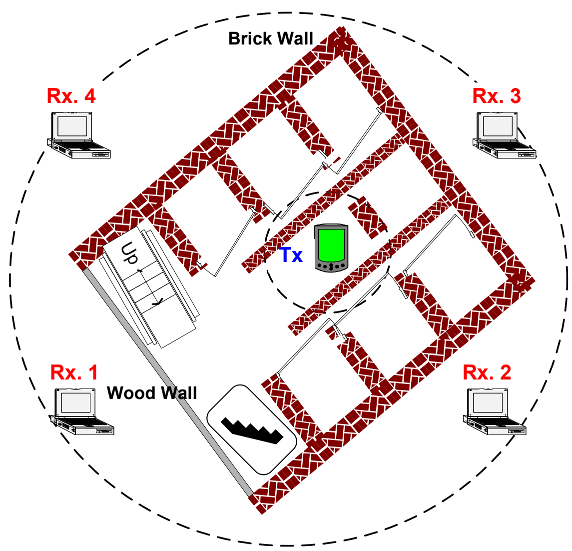

Figure 9 Indoor Positioning in Office Area

Figure 10 shows the delay for various wall thicknesses due to different dielectric constants that will depend on the building material.

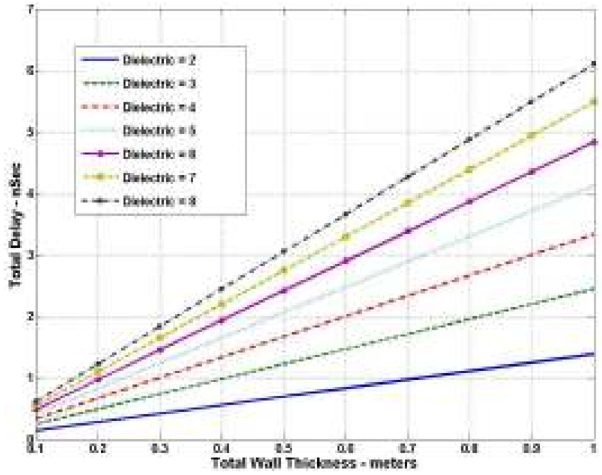

Figure 10 Wall Thickness vs. Signal Delay for Various Dielectric Constants

6. CONCLUSION

From the error analysis, it is clear that in addition to the well known error sources multipath and NLOS, the dielectric properties of the building materials add to the positioning error. To the best of author's knowledge no indoor positioning papers recognize and address this issue. The indoor environment typically has more than two walls and this could lead to indoor positioning errors of more than 3m, depending on number of walls, the dielectric constant of the wall material, frequency and weather. The frequency dependent and weather dependent dielectric constant characterization for commonly used building materials are unavailable. There is a need to perform tests that will result in such data which can then be used to calibrate the system thus minimizing the errors on indoor position estimates due to building dielectric material properties. Thus not so well known source of error needs to be considered in designing an indoor positioning system if accuracies of less than 3m are desired.

11. REFERENCES

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BIOGRAPHY

Hemish K. Parikh is a research assistant at Center for Advanced Integrated Radio Navigation (CAIRN) at Worcester Polytechnic Institute. He received his Bachelors degree in Electronic and Telecommunication Engineering form Bombay University, India in 2000 and M.S degree form University of Missouri - Columbia in 2002. He is currently pursuing his PhD in the ECE department at WPI. His research interest includes indoor precision position location systems and is currently involved in developing RF transmitter and receiver system for precise positioning systems. He is actively involved in design, development and testing of RF systems, for indoor navigation. He is a student member of IEEE and ION.

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Dr. William R. Michalson is a Professor in the ECE Department at the Worcester Polytechnic Institute where he performs research and teaches in the areas of navigation, communications and computer system design. He supervises the WPI Center for Advanced Integrated Radio Navigation (CAIRN) where he is developing a Public Safety Integration Center focused on the integration of communications, navigation and information technologies for public safety applications. His research focuses on the development, test, and evaluation of systems for both civilian and military applications with a special emphasis on techniques focused on indoor, underground or otherwise GPS-deprived situations. Prior to joining the faculty at WPI, Dr. Michalson spent approximately 12 years at the Raytheon Company where he was involved with the development of embedded computers for guidance, communications and data processing systems for space borne and terrestrial applications.