ERROR MECHANISMS IN AN RF-BASED INDOOR POSITIONING SYSTEM

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ABSTRACT

An RF-based indoor precise positioning system being developed for fire fighters is discussed in this paper. The paper will discuss system level overview of the RF prototype and will discuss the NLOS field tests and indoor positioning results using this RF prototype. The position estimation algorithm used is based on Time Difference of Arrival (TDOA) for a multicarrier signal. An error budget for such an RF-based indoor positioning system is presented in this paper with more insight to the sources of errors. Multipath and NLOS conditions indoors are well known error sources but there also exists another not so well known but major sources of error which are due to dielectric properties of the building materials. Basic simulations are presented to better understand the effect of the dielectric properties of building materials on indoor position estimates.

Index Terms— Indoor Positioning, RF System, Dielectric Properties, Positioning Errors

1. INTRODUCTION

Figure 1 provides an overview of the envisioned RF-based precise positioning system being developed at Worcester Polytechnic Institute. The goal 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 fighters in and around a burning building, carry an RF transmitter that continuously transmits a radio signal. The radio signal used is a MultiCarrier-UltraWideband (MC-UWB) signal structure as it is much easier to adapt to existing spectral assignments [1, 2]. This MC-UWB signal is then received by the RF 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 TDOA based position estimation algorithm. This position information of each fire fighter is then sent to a central command and control display from where emergency exit guidance can be provided to the fire fighter in trouble. 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 the position information the guiding vision is to also provide; health and vital sign information along with environment and temperature monitoring.

Figure 1: Indoor Positioning System Overview

2. RF SYSTEM ARCHITECHURE

The system architecture of the developed RF-based prototype system is shown in Figure 2. 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, undergoes digital to analog conversion, is upconverted to the required RF frequency, and is continuously transmitted. 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 the transmitter's position estimate.

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.

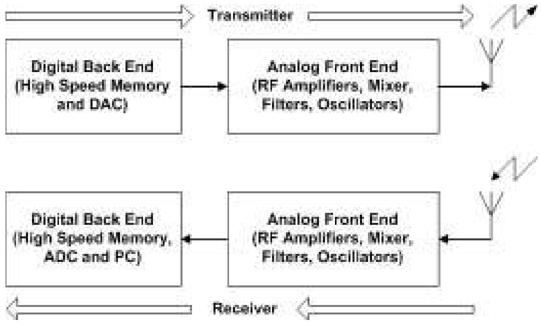

Figure 2 RF System Architecture

The 148MHz RF transmitter front end consists of 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 3. The RF transmitter front end was optimized to achieve magnitude flatness of approximately +/-1dB flatness across most of the 550MHz to 698MHz spectrum.

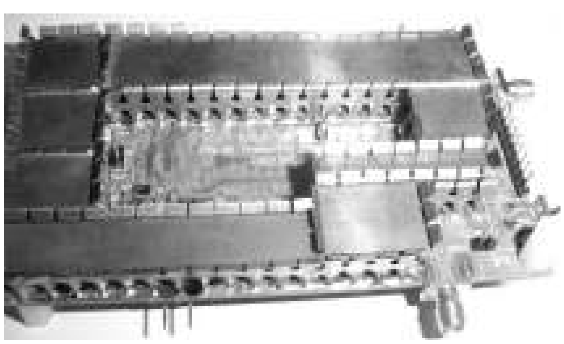

Figure 3 RF Transmitter Front End PCB

The 148MHz RF receiver front end 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 RF band pass and the low pass filters are of a custom-made 7-section LC filter configuration. The selection of the LNA is very 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 RF 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 at the receiver. Similar to the RF front end PCB shown in Figure 3, custom made RF receiver PCB was also designed. The RF receiver front end was also optimized to achieve magnitude flatness of approximately +/-1dB flatness across the 550MHz to 698MHz spectrum.

3. NLOS INDOOR POSITIONING FIELD TEST AND RESULTS

The 148MHz RF 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. The field tests were performed at various indoor locations, one of which is shown below in Figure 4, which is approximately a 20mx20m brick walled building. The test setup uses 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 4, a total of 16 receiving antennas were carefully placed around the three sides of the brick building, to optimize the geometry.

Figure 4 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 [3] to separate the direct path from the multipath. Also these tests were conducted using spectrally clean and optimized RF hardware, and the signal bandwidth used was a 148MHz MC-UWB signal. 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 maintain 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 sources of errors that could be causing the observed 3m to 6m errors in position estimates.

4. ERROR SOURCES

After extensive simulations, bench tests and field tests the error sources and their contribution in a field tests discussed above are quantified in Table 1. The discrepancy in the transmitter and receiver sampling clocks results in degrading the positioning estimate. Using the 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. The presence of receivers on only three sides of the brick building and not all four sides contributes to errors up to 0.3m. The antenna polarization, radiation pattern and antenna type also affects 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. 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 0.5m or more. This source of error is due to building material dielectric properties and needs to be accounted in the error analysis. The building material dielectric properties result in adding delay to the transmitted signal and the RF wave inside the material is going to be slower than the propagation of the RF wave in free space.

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 meter**	

The materials used in construction of a building do have an effect on the position estimation inside a building. The most common building materials are concrete, bricks and wood. Basic simulations [4] were performed to better understand the expected errors due to building materials dielectric properties. Consider a NLOS, multipath free example of positioning inside a brick building as shown in Figure 5. As shown in Figure 5, the four receivers are outside the building and are equidistance 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 5 was 0.923m.

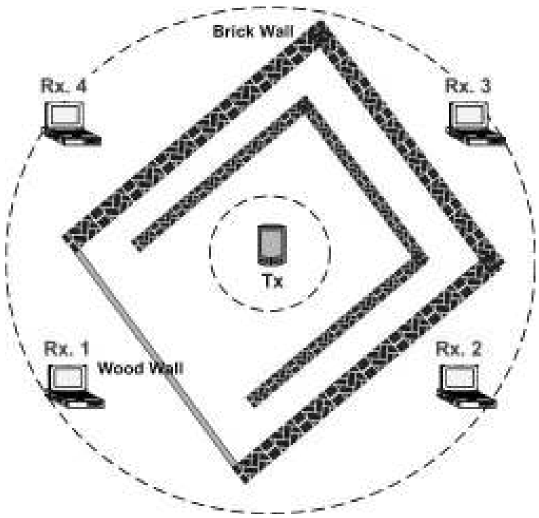

Figure 5 Indoor Positioning in Brick Building

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 frequency, the dielectric for concrete varies from 26 to 10 over 50MHz to 1GHz [5]. Figure 6 shows the delay for various wall thicknesses due to different dielectric constants that will depend on the building material.

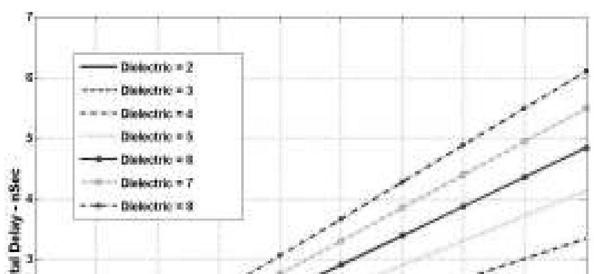

Figure 6 Wall Thickness vs. Signal Delay for Various Dielectric Constants

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 2-3m, 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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