UWB Channel Measurements and Modeling for Positioning and Communications Systems in the Operating Room

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Abstract — The prevalence of UWB has greatly increased in recent years for numerous applications in dense multipath indoor environments. We have measured and modeled the ultra-wideband (UWB) channel environment found in the operating room which can be used to examine its effects on the performance of UWB positioning and communications systems. Frequency and time domain measurement data obtained in the operating room in both live (during orthopedic surgeries) and non-live scenarios was fit to the IEEE 802.15.4a channel model. Simulation data was then obtained through the IEEE 802.15.4a channel model for characterizing the operating room environment. Electromagnetic interference was also measured in the operating room. Even in the dense multipath environment found in the operating room, UWB shows strong potential for multiple applications including wireless tracking for surgical navigation, incorporation into low power ex vivo and in vivo bio-sensors, and high data rate wireless telemetry of critical bio-signals including ECG, EMG, blood pressure, and body temperature.

Index Terms — Ultra-wideband, medical environment, channel modeling, wireless positioning, digital communication.

I. INTRODUCTION

Ultra-wideband (UWB) technology has gained widespread popularity in both research and industry since its consideration and acceptance for standardization by the Federal Communications Commission in 1998 and 2002 [1]. As shown in Fig. 1, the allocated spectrum in the United States is much less restrictive than Europe since the whole 3.1-10.6 GHz band is available with no detect and avoid requirements. As mentioned in [2], UWB has gained widespread use in asset tracking applications where integration of UWB real-time location systems (RTLS) with other technologies including RFID, wireless local-area-networks (WLANs), GPS, and Wi-Fi is the current trend driving the technology behind integrated asset tracking solutions for large scale process optimization, as shown in Fig. 2. The projected total revenue in the RFID market in 2009 is 5.56 billion USD. This includes ample growth opportunities for UWB RTLS since many of the new target areas reside indoors where multipath interference becomes a major concern [3].

UWB systems have been designed and targeted for various medical applications given its robustness to dense multipath interference found in hospital environments as shown in Fig. 3. For example, we have developed a high accuracy UWB positioning system for tracking in surgical navigation [4]. Low power CMOS chips adhering to the IEEE 802.15.4a standard exist [5] and provide an attractive solution for positioning and communication in body area networks (BANs) [6-7]. UWB communication is needed in
high data rate telemetry applications such as multi-channel neural recording systems which require data rates in excess of 100 Mbps [8]. Finally, Time Domain Corp. utilizes UWB tracking of patients, staff, and medical equipment in a hospital environment to optimize workflow processes and track people and assets via its commercial tracking system [9].

This paper is organized as follows: Section II introduces the operating room channel by outlining the frequency and time domain experimental setups and corresponding experimental and simulation results to quantify the multipath interference observed. Section III outlines an experiment used to measure electromagnetic interference in the operating room. Finally, Section IV concludes.

II. OPERATING ROOM UWB CHANNEL

The operating room presents a formidable metallic environment with a dense number of scatterers when considering wireless positioning and communication. For this reason, most narrowband systems exhibit poor and typically unsatisfactory performance in these types of environments [10]. As mentioned in [10], UWB RTLS outperform competing technologies in terms of performance of indoor positioning systems in operating room environments. Given the large amount of metallic interference, we need an accurate characterization of this environment to be able to design and simulate its effects on system performance. We have performed both time domain and frequency domain experiments in order to obtain data related to a number of factors relevant to characterizing the operating room channel which includes: frequency dependent pathloss, small scale fading, power delay profile, number of multipath clusters, intra-cluster decay rate, etc. This data was fit to the IEEE 802.15.4a channel model (a comprehensive overview can be found in [11]). Figure 4 shows the block diagram of the experimental setup for obtaining time domain data where both Vivaldi and monopole antennas are used to analyze the effects of the antenna on channel and system performance. Figure 5 shows a picture of the experimental setup in the operating room when no surgery is taking place while Fig. 6 shows the layout of the operating room for obtaining measurement data during the orthopedic surgery.

Results from these experiments were fit to the IEEE 802.15.4a channel model and can be found in [4]. The operating room environment is most similar to the residential line-of-sight (LOS) or CM1 in terms of pathloss while it is most similar to the industrial LOS or CM7 in terms of power delay profile and intra-cluster decay. As shown in Fig. 5, the presence of metal tables, metal lamps, and a large metallic wall contributed greatly to the multipath interference measured experimentally and simulated with the IEEE 802.15.4a channel model. Using the IEEE 802.15.4a channel model, UWB positioning and communications systems can be designed for the operating room environment (examples of high data rate and wireless sensor network UWB technologies can be found in [12-13]).
The operating room channel contains dense multipath interference which can be observed experimentally and quantified with the IEEE 802.15.4a operating room channel model. Figure 7 shows an experimentally received signal in the time domain where four main multipath peaks are observed in the first cluster. These multipath peaks are caused by reflections off of metal tables, equipment, lights, and a large metallic wall close to the operating table. Figure 8 shows a simulated impulse response of the IEEE 802.15.4a operating room channel. Three distinct multipath clusters are observed. The initial cluster has a fast decay rate while the subsequent two clusters have slower decay rates. The overall power of the received signals decays quickly when comparing the peak power in the first, second, and third multipath clusters. Figure 9 shows a time extended pulse that was simulated with our comprehensive simulation framework described in [14-15]. Our operating room channel model was added to the pulse train seen at the UWB receiver. A transmitter-receiver distance of 1 m was used to add pathloss to the received signal. As shown in Fig. 9, a LOS pulse is observed. This pulse contains distortion. Dense multipath effects are observed after the LOS pulse. Only with an accurate detection of the leading-edge of the LOS pulse can millimeter ranging accuracy be achieved in these types of dense multipath indoor environments. The OR environment presents many design challenges when targeting high data rate digital communication and high accuracy localization UWB systems.

Fig. 7. Experimental received time domain signal with noticeable multipath interference caused by metal tables and walls in the operating room.

Fig. 8. Simulated operating room channel impulse response using the IEEE 802.15.4a channel model and the parameters defined in [4] where three separate multipath clusters can be observed, each with progressively less power. The first cluster has a large intra-cluster decay rate while the latter two clusters exhibit slower decay rates.

Fig. 9. Simulated time extended pulse after the analog-to-digital converter at the UWB receiver where a 1000x expansion factor increases the pulse width from 300 ps to 300 ns. Noticeable multipath effects are caused by the operating room channel (10µs corresponds to 10ns in Fig. 8 due to time expansion by the sub-sampling mixer).

### III. ELECTROMAGNETIC INTERFERENCE IN THE OPERATING ROOM

Electromagnetic interference (EMI) was measured over a large frequency band (200 MHz – 26 GHz) in the OR during four separate orthopedic surgeries. Figure 6 shows a layout of the dual OR. Two ORs allow a faster turn-around time in completing the four surgeries. Besides the operating table, numerous other pieces of medical equipment were present during the surgery including an anesthesia machine, ventilator, surgical lamps, various monitoring equipment, visualization screens, carts containing necessary orthopedic surgical tools, drills, etc. The combination of people and medical equipment closely packed into the OR creates a dense multipath indoor environment that can greatly disrupt standard RFID tracking systems.

Various hardware was needed to get accurate measurements across the wide band of 200 MHz – 26 GHz. Table I summarizes all of the equipment needed in running this experiment. It should be noted that all reported gain and noise figure values are averages across the frequency range of operation. Figure 10 shows the four antennas used to cover the entire frequency range. The standard setup for each of the frequency bands measured included an antenna, two stages of amplification, and a spectrum analyzer for visualization. Commercial off-the-shelf components were used whenever possible. Figure 11 shows the frequency band from 800 MHz – 3 GHz. A number of different signals were found in this frequency range. The two
strongest signals, which were found at 872 MHz and 928 MHz, correspond to CDMA-2000 uplinks and downlinks. The peak at 1.95 GHz corresponds to a US cellular band. Finally, the peak at 2.4 GHz is caused by WLAN and/or Bluetooth components.

Table I: Hardware used in broadband operating room EMI measurements.

<table>
<thead>
<tr>
<th>Device</th>
<th>Model #/ Type</th>
<th>Frequency</th>
<th>Gain (dB)</th>
<th>Noise Fig. / Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNA</td>
<td>Mini-circuits ZX60-3011</td>
<td>400 MHz – 3 GHz</td>
<td>10</td>
<td>1.6 dB</td>
</tr>
<tr>
<td>LNA</td>
<td>Hittite HMC465</td>
<td>DC - 20 GHz</td>
<td>15</td>
<td>3.5 dB</td>
</tr>
<tr>
<td>LNA</td>
<td>Hittite HMC517</td>
<td>17 – 26 GHz</td>
<td>19</td>
<td>2.7 dB</td>
</tr>
<tr>
<td>Antenna - A</td>
<td>TDK MBA-2501 Biconical</td>
<td>250 MHz – 1 GHz</td>
<td>23</td>
<td>Omni-directional</td>
</tr>
<tr>
<td>Antenna - B</td>
<td>Kathrein Scala 800-10249 Disc</td>
<td>824 – 960 MHz, 1.425 – 3.6 GHz, 5.15 – 6 GHz</td>
<td>2</td>
<td>Omni-directional</td>
</tr>
<tr>
<td>Antenna - C</td>
<td>Double ridged TEM horn</td>
<td>1 – 18 GHz</td>
<td>8</td>
<td>Directive</td>
</tr>
<tr>
<td>Antenna - D</td>
<td>Vivaldi array – 4 element</td>
<td>18 – 26 GHz</td>
<td>10</td>
<td>Directive</td>
</tr>
<tr>
<td>Spectrum Analyzer</td>
<td>Agilent E4407B ESA-E</td>
<td>9 kHz – 26.5 GHz</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Fig. 10. Antennas used in OR measurements: a) biconical, b) multiband disc, c) broadband TEM horn, d) 4-element Vivaldi array.

IV. CONCLUSION

Time domain and frequency domain experimental data was obtained in the operating room to characterize the OR by fitting it to the IEEE 802.15.4a channel model and also by measuring the EMI present in an OR during surgery. This serves as a first step in optimizing UWB positioning and communications systems for the OR environment.

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