Capacity Measurements for Body Mass Index Dependent Ultrawideband MIMO BAN Channels

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Abstract—Information theoretic analyses have shown the potential for a significant capacity gain in wireless systems by use of multiple antennas at both transmitter (TX) and receiver (RX) ends in various propagation channels. These channels are typically characterized by scenario-specific channel sounder systems. In this paper, we present a detailed description of a developed Ultrawideband (UWB) 4 x 4 multiple-input-multiple-output (MIMO) channel sounding system and capacity measurements results for Body area network (BAN) channels. The main focus of the investigation is the study of the impact that Body Mass Index (BMI) of a human being has on wireless body area network (BAN) measurement results in an anechoic and indoor Lab environments. We found the capacities values to be different for various BMI categories. This paper also describes measurements done to examine how tissues and fabric influence (or distort) the radiation pattern of an antenna when in close proximity to it.

I. INTRODUCTION

With the growing demand for new, ever more data hungry wireless applications, MIMO communication has been embraced as a solution that provides better Signal-to-noise ratio (SNR), higher robustness and data rate, through beamforming, higher diversity order, and spatial multiplexing [1]. This multi-antenna approach has also been suggested for wireless Body Area Network (BAN) applications, which are in need of especially the latter two advantages. Furthermore, ultrawideband (UWB) transmission technology is attractive for BAN systems due to some of the qualities it affords, such as low-power, high data rate, and robustness to fading [2]. UWB signals are defined as either having more than 20 % relative bandwidth or more than 500 MHz absolute bandwidth [3] and are permitted to operate in the 3.1-10.6 GHz frequency band by the Federal Communications Commission (FCC) in the USA.

Electromagnetic (EM) waves in a BAN transverse the human body either by surface waves or diffraction mechanisms [2] and it is expected that human body tissues will have a significant effect on the propagation especially when various body types (with different dimensions and tissue properties) are considered. The Body Mass Index (BMI) is a measure of human body fat based on height and weight [4] and can thus be anticipated to be a contributing factor to the characteristics of any on/off body wireless propagation. The effect of BMI on BAN should hence be clearly understood. For example in medical applications, modeling the BANs on people with very high BMI is particularly important, since it is exactly this group of users for whom medical BANs are especially relevant [5]. However, most previous measurements and models only considered test subjects with BMI < 25 i.e., low or medium BMI.

In this paper, we present details about our 4 x 4 UWB MIMO array channel sounding system which was developed and used to perform BAN channel measurements in an anechoic and indoor Lab environment with consideration for different BMI categories. The influence of tissues in combination with fabric on antenna radiation pattern due to its proximity is explored in this work, together with the antenna calibration procedure. We finally provide capacity results for UWB MIMO systems operating in different channels measured for various BMI categories in the aforementioned environments. We provide a short description about the measurement campaign itself and present some of the obtained results. The complete channel measurement results and an associated stochastic model are provided in [5] and [6].

The rest of the paper is organized as follows. The system description is provided in Section II. Tissue influence on antenna radiation pattern is discussed in Section III. The propagation channel measurement campaign is discussed in Section IV. Results are provided in Section V, while conclusions are inferred in Section VI.

II. SYSTEM DESCRIPTION

We first describe our channel sounder system, which was specifically designed and assembled for characterizing UWB BAN channels. The complete BAN channel sounder setup is shown in Fig. 1.

A. Vector Network Analyzer

The measurements were performed in the frequency domain using a vector network analyzer (VNA, Agilent 8720ET) . This is a two-port device, which provides the complex channel transfer function of the propagation channel. This VNA was calibrated along with two 2.7 m long coaxial cables (at TX, RX ends) from the antenna feed points of the coaxial cables, and a stepped frequency sweep was conducted for 801 frequency points within a range of 2 - 10 GHz. The entire frequency sweep time for each measurement was 1.62 s.

B. UWB antennas

Using an in-house developed XY3 Trapeziodal monopole omni-directional UWB antennas [7], a 4-element switched uniform linear antenna (ULA) array configuration was implemented at both the TX and RX ends. The antennas were placed...
7.5 cm apart in the linear array configuration (see Fig. 1) while mounted so they are vertically polarized parallel to the body surface and kept at 0.95 cm from the body.

**C. Switch and related equipment**

The MIMO sounder is based on a switched array principle, i.e., the TX and RX ports of the VNA are connected sequentially to one antenna element at a time, through fast switching RF Pin Diode switches. We use a Pulsar Microwave (SW8RD13) reflective RF switch with an 8-port output (SP8T), 100 ns switching speed, insertion loss of 3.5 dB and the operating frequency range of 0.5 - 12 GHz. This RF switch was also calibrated before use.

To facilitate the sequential switching in the channel sounding system, a control circuit was built to handle the toggling between the output ports of the RF switch. The control circuit was activated/deactivated by a Labview script running on a personal computer (PC) present in the setup.

A PC running a Labview software was used in activating the control circuit of the RF switch as well for the data acquisition and storage from the VNA.

**D. Harness**

The antenna arrays were placed on a harness that was worn by the test subjects on their bodies, harness was worn on the body to avoid the antenna directly contacting the body surface as this would cause degradation in performance of the antenna and significantly influence the pathloss. Due to the nature of the harness, reproducibility was generally of a concern as discussed in detail below.

**III. TISSUE INFLUENCE ON ANTENNA PATTERN**

In BAN models, antennas are often considered to be part of the propagation channel. Effects of antenna proximity to the body has been extensively studied in the literature [8]. This is especially important since antenna proximity to the human body could in essence distort the radiation characteristics of the antenna. In the literature, the UWB antenna radiation pattern has been described as frequency varying [9] while the electromagnetic properties of human body tissue has also been noted as frequency varying in [10]. To confirm the possibility of the aforementioned radiation pattern distortion in our work, as well as a sanity check, we studied the impact that materials such as meat, cotton fabric and a combination thereof (see Figs. 4(a) - 4(c)) have on the radiation characteristic of the omni-directional UWB antenna when placed in contact (or close proximity) with it. We performed a radiation pattern calibrating of the XY3 antenna (used in our setup) over its azimuth angles and frequency range of operation. This calibration was also repeated with tissue (meat) and cotton fabric attached to the antenna. The antenna calibration procedure is discussed below.

**A. Antenna Calibration Procedure**

The antenna calibration was performed in an RF shielded anechoic chamber (9.14 x 4.57 x 4.57 m) at the UltraLab wireless test facility at the University of Southern California (USC). A custom setup was built (see Fig. 3) such that the antenna element was attached to a mounting arm placed on a dual-axes azimuth/elevation rotor (OrbitFR AL-4370-1) operated with a rotor controller (OrbitFR AL-48063-C). The center of the antenna was aligned with the intersection of azimuth and elevation rotation axes. A UWB horn antenna was used as a reference/probe transmit antenna for the co/cross- polarization (vertical/horizontal) measurements. For each orientation the S21 parameter between the reference antenna and the antenna element being calibrated was measured over the 2 - 10 GHz frequency range for 801 points using the VNA. All equipment were connected to a PC and controlled by a Labview script running on the PC. An azimuth angle ranging from $-180^\circ$ to $180^\circ$ was measured at 3 degree incremental step.

The radiation pattern calibration of XY3 antenna was performed with the following configurations:
1) XY3 as a standalone antenna
2) XY3 place on the meat
3) XY3 placed on meat that was covered with fabric

The specification (dimensions and type of the materials) of the meat and cotton used are presented in Table I.
B. Antenna Calibration Results

The radiation pattern (complex antenna response) obtained from our calibration using the different configuration are shown in Figs. 2(a) - 2(c) below. It is clearly observable from these figures that the radiation pattern looks mostly omnidirectional as expected for the standalone configuration in Fig. 2(a) at all frequencies, while Fig. 2(b) reveals both a frequency and spatial preference of the radiation pattern especially at higher frequencies. The frequency-dependency observed is as a consequence of the tissue attached to the antenna, which exhibits a loss at higher frequency while the spatial preference is as a result of the meat being attached to the back of the antenna hence making the radiation somewhat directional. Also, Fig. 2(c) exhibits the selectivity in frequency as well, with a more distinct spatial preference when compared to Figs. 2(a) and 2(b). This is a consequence of the cotton fabric used in the setup.

While the piece of meat cannot truly replace the effects caused by the human body due to uniqueness of the human tissue dielectric constant values [11], [12], it does however confirm that the radiation characteristics could in fact be affected when in close proximity to any tissue (in this case - meat) and also suffer a related (though smaller) effect due to fabric. Therefore, it is important to keep this observation in mind when interpreting the result from this work.

IV. Propagation Channel Measurement

Our assembled UWB MIMO channel sounder was used to perform BAN measurements for different on-body channels (see Table III with antenna placement shown in Figs. 5(a) - 5(g)) for various BMI categories. The BMI categories/classification [13] are provided in Table II below.
A total of 60 male subjects (20 per category) with ages 18 years or older with various BMIs were considered. We could not conduct experiments with female subjects since no female research personnel qualified to work on this Institutional Review Board (IRB) - approved project was available to work with female test subjects.

TABLE II: International Classification according to BMI

<table>
<thead>
<tr>
<th>Category</th>
<th>BMI Value</th>
<th>Classification</th>
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<tbody>
<tr>
<td>1</td>
<td>18.5 - 24.9</td>
<td>normal</td>
</tr>
<tr>
<td>2</td>
<td>25 - 29.5</td>
<td>overweight</td>
</tr>
<tr>
<td>3</td>
<td>≥ 30</td>
<td>obese</td>
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TABLE III: Channels measured on the body

<table>
<thead>
<tr>
<th>Channel</th>
<th>Location</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Front-to-Front (F2F)</td>
</tr>
<tr>
<td>2</td>
<td>Front-to-Shoulder (F2S)</td>
</tr>
<tr>
<td>3</td>
<td>Front-to-back (F2B)</td>
</tr>
<tr>
<td>4</td>
<td>Front-to-Hip (F2H)</td>
</tr>
<tr>
<td>5</td>
<td>Hip-to-Shoulder (H2S)</td>
</tr>
<tr>
<td>6</td>
<td>Hip-to-Back (H2B)</td>
</tr>
<tr>
<td>7</td>
<td>Hip-to-Leg (H2L)</td>
</tr>
</tbody>
</table>

The measurements were conducted at the aforementioned Ultra Lab facility USC in Los Angeles, CA, USA. The experiments were performed in both an anechoic chamber and indoor lab environments. The anechoic chamber serves as a controlled environment with few or no reflection while the indoor lab is a 13.10 x 15.24 x 6.09 m room mostly populated with metallic work benches, plastic chairs and computers, hence it constitutes a scatterer-rich environment. Due to space limitation, we cannot provide an exhaustive discussion about the measurement campaign in this paper, however, additional details about the channel measurements and modeling are provided in [6] and [5]. A key assumption in our measurement is that the channel is static, which is fulfilled if there are no posture variations/ movements from the human subject or moving scatterers in the environmental, we thus made sure of this in our experiment. However, it is important to note that due to the breathing of the human subject and the harness worn during the channel measurements, variations with root-mean-squared (rms) deviation of 0.27 dB were observed in the received power (over frequency) when conducting consecutive (repeated) measurements. This variation was investigated further by performing successive measurements while the harness was placed on a test dummy, which is a still/non-breathing object. We observed a variation with rms deviation of 0.07 dB in power received; this we attribute to measurement noise. Hence, it is important to keep this in mind when interpreting our results.

V. RESULTS

We analyzed the MIMO channel capacities for various on-body channels measured for different BMI categories in the anechoic and indoor lab environments. The MIMO channel capacity was derived as typically done for frequency-selective channels by using (1) below, which is based on the assumption that the TX does not have channel state information (CSI). This capacity is computed such that the overall channel capacity per unit bandwidth is the average (in an OFDM-like
We developed and calibrated a UWB MIMO channel sounder system and conducted an extensive BAN channel measurement campaign to study the impact that BMI has on the capacity of MIMO on-body channels. We found the mean capacity values to differ considerably (up to 10 b/s/Hz in some channels) between BMI categories, with higher capacity values obtained in BMI 1 and 2 categories than in BMI 3. We also investigated the influence that tissue and fabric have on the radiation pattern of an antenna when in close proximity to it. We found that there is in fact a spatial and frequency selectivity that occurs as a consequence of the tissue and fabric. The outcome of our measurements emphasizes the fact that BMI values should most certainly be factored in any BAN channel model being considered for system simulation and design.

VI. CONCLUSION

The authors would like to thank Prof. Fredrik Tufvesson for providing antennas used for earlier version of the experiment. They would also like to thank Phil Philip for helping with the preliminary measurement setup, Dr. S. Niranjayan for helping with circuit design. Finally, the authors would like to thank the USC Institutional Review Board (IRB) for granting the permission to conduct the experiment.

REFERENCES


### Table IV: Channel Capacity values for various channels and BMI categories for TX SNR = 64 dB

<table>
<thead>
<tr>
<th>BMI</th>
<th>Mean Capacity (b/s/Hz)</th>
<th>Outage Capacity (b/s/Hz)</th>
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<tbody>
<tr>
<td></td>
<td>F2F</td>
<td>F2B</td>
</tr>
<tr>
<td>BMI 2</td>
<td>19.13</td>
<td>20.61</td>
</tr>
<tr>
<td>BMI 3</td>
<td>15.65</td>
<td>13.71</td>
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