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Limb Joint Effects on Signal Transmission in Capacitive Coupled Intra-Body Communication Systems

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Abstract— **This paper contributes empirical measurements towards an understanding of signal attenuation in intra-body communication (IBC) systems due to limb posture effects. Recent studies have shown a degradation of transmission signals for IBC transmissions between limb segments, but these degradations have yet to be quantified with respect to relative limb position and within the transmission frequency range from 300 KHz to 200 MHz. We examine the impact of limb position specifically the effect of elbow joint flexion and extension into account using a portable vector network analyzer. The results presented indicate that the signal attenuation is larger in the case of extension, i.e., when the angle between forearm and upper arm increases. The minimum attenuation was 20.64 dB and 24.81 dB for the fix distance of 15 cm between transmitter and receiver electrodes and the joint angle of 45 and 180 degree respectively. It was found that attenuation decreased at an approximately linear rate over 300 KHz to 100 MHz and increased over the frequency range from 100 MHz to 200 MHz for the input signal frequency range from 300 KHz to 200 MHz. It was concluded that the minimum attenuation for the range of flexions and extensions occurred in the range 80-100 MHz. Future work will explore theoretical models to explain the observed results.**

I. INTRODUCTION

A wireless monitoring system permits healthcare workers to assess patients' health without interrupting their day to day life. Wireless radio frequency (RF) data transmission now allows portable medical devices to monitor a subject's health where ever there is network connectivity. A major drawback of wireless RF propagation for miniaturized medical monitoring devices is power consumption which requires batteries and is the major limiting factor for continuous monitoring. For example, ZigBee provides a wireless solution targeted at monitoring and control applications in which power consumption is around 30 mW [1]. Either longer lasting batteries or a new generation of low power wireless communications is required to improve the efficacy of portable medical monitoring systems. Intra-Body Communications (IBC) is a novel non-RF data communication technique using the human body itself as the transmission medium or channel. Research has shown that IBC is capable of low transmission power below 1 mW and data rates of more than 100 Kbit/s [2]. This suggests IBC is an energy efficient communication approach.

Since different body parts might take various postures during the human body movement, wireless communication systems (RF or non-RF) should function well when the body is in motion. Although some attempts have been reported for body motion effects in RF communication systems recently, body motion in IBC systems have not been considered widely. According to Corroy *et al.* [3] the data transmission between on-body nodes and also off-body nodes within Industrial, Scientific and Medical (ISM) frequency bands (900 MHz to 2.4 GHz) is not reliable while the body is in motion. On the other hand, work has shown that in the ultra-wideband (2.5 to 5.5 GHz) body area propagation channel, there is a negligible effect on the received power when the arm is moving to the front and side of the body [4]. The effect of body motion in IBC is examined in [5] through measuring impedance changes while the body was in motion. Although the authors mention that the influence of body motion was not significant, the details of their measurement results were not provided. Schenk *et al.* [6] also found that body movement causes variation in channel attenuation. Using the capacitive coupling method they investigated walking and standing while moving the right arm. The results from walking posture through IBC method have shown signal attenuation up to 2.5 dB below the frequency of 60 MHz. However, none of these studies have addressed precise details of body motion which is particularly important because whole body movements are effectuated by continual joint motions.

This paper presents *in vivo* experimental results toward understanding particular body movement effects on signal attenuation in IBC systems. The frequency range of our study goes from 300 KHz to 200 MHz.

II. METHODS

A. *Capacitive Coupling Approach*

IBC can be classified into two primary coupling techniques i.e. Capacitive coupling (Electric field) and Galvanic coupling (Waveguide) [2], [7].

Data transfer by capacitive coupling through the human body was first proposed by Zimmerman as a transmission methodology for Personal Area Networks (PAN) [2]. In the capacitive coupling method, the human body acts as a transmission medium by making use of the electric field (EF) around the body. In this method only one of the electrodes (signal electrode) of the transceiver and receiver is attached to the body while the other electrode (ground electrode) is floating. The signal electrode of the transmitter induces the electric field in to the human body. The body acts as a perfect conductor and directs the signal to the

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receiver. The signal is generated between the body channel transceiver by completing the current loop through the external ground.

The relatively higher data rate (i.e. 10 Mbit/sec [8]) is the most beneficial feature in the capacitive coupling method due to lower channel attenuation. In contrast the galvanic coupling method has been reported to have higher channel attenuation due to the dielectric properties of the human body leading to relatively low data rates (i.e. 64 Kbit/sec [7]). In this work, we examine the limits of the capacitive coupling approach in the presence of joint-segments. Although some results have suggested that body movement considerably affects data transmission, this has not as yet been quantified. Quantification of signal attenuation in the capacitive coupled methods will improve understanding of this technology's limits.

B. Measurement

Body movements are mainly permitted by joints where two bones make contact. Joint anatomy is slightly different from limb segments. Joints are protected by cartilage and they have smaller amount of muscle compared to other parts of human body. Tendons of several muscles cross the joint and provide secure human body motions [8]. This means that the presence of a joint in a communication pathway has an effect on signal propagation because there is a sudden change in the dielectric properties of different tissue layers in the propagation path. Understanding the dielectric properties of joint layers will be helpful in further analysis of the signal propagation, reflection, and attenuation. In this work, we present empirical results to demonstrate the effect of joints on signal attenuation.

We evaluate the influence of joint angles by making use of scattering parameters (S-parameters). S-parameters describe the operation of a two-port circuit network. As shown in figure 1, the two-port circuit network is composed of transmitter electrodes, human body as a transmission medium, and receiver electrodes. S-parameters measure the signal propagation characteristics within the body in terms of signal power. Reflected signal power are measured by S_{11} and S_{22}, also known as reflection coefficients. S_{21} and S_{12} refer to signal transmission from transmitter electrodes to receiver electrodes, and are known as forward transmission and reverse transmission coefficients respectively.

Attenuation or path loss factor is a general term that refers to any reduction in the strength of a signal between the transmitter and receiver electrodes. The attenuation factor is the ratio of the receiver power to the transmitter power calculated as:

$$\text{Attenuation} = 20\log_{10}\left(\frac{V_{\text{receiver}}}{V_{\text{transmitter}}}\right) \qquad (1)$$

where, $P_{\text{transmitter}}$ and P_{receiver} are signal power at the transmitting side and the receiving side, respectively. The channel attenuation generally varies with frequency. In this work, the human body channel can be characterized by measuring the signal attenuation through the human body in the capacitive coupling IBC.

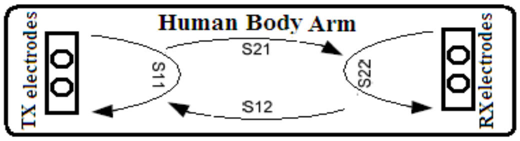
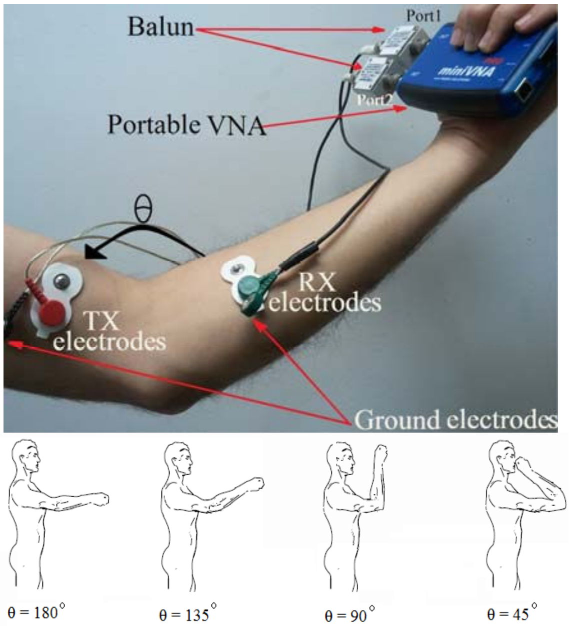


Fig.1. Measurement setup associated with S-parameters

C. Measurement setup

The measurement setup for channel characterization is shown in figure 2. Self-adhesive silver/silver chloride (Ag/AgCl) electromyography (EMG) dual electrodes (Noraxon) were employed in the transmitter and receiver side. We used EMG snap leads as connecting wires. A portable battery powered vector network analyzer (miniVNA Pro) was used to measure the scattering parameters (S-parameters) of the IBC system to characterize it. A pair of balance-unbalanced (baluns) transformers with two ports was placed between the electrodes and miniVNA. Baluns were used to decouple the miniVNA ports from each other. They also prevent the parasitic return path from being shorted to the common voltage of the miniVNA battery.



θ = 180°   θ = 135°   θ = 90°   θ = 45°

Fig. 2. The measurement setup; θ is angle between upper and lower arm, RX and TX electrodes are attached to lower and upper arm respectively.

In order to measure the attenuation, port 1 of miniVNA was considered as the transmitter and port 2 the receiver. The miniVNA was calibrated to induce AC current to the human body below 1 mA, manually. According to the exposure guidelines of the International Commission on Non-Ionizing Radiation Protection (ICNIRP), this induced current is 20 times below the maximum allowed contact current [10]. In addition, the input signal power was selected based on the study of World Health Organization (WHO) on the possible health effects of exposure to electromagnetic field [11]. The source power from the miniVNA was fixed to a very lower input power of just 0 dBm (= 1.0 mW) for further safety.

D. Protocol

Considering an average weight of 65 Kg, the maximum transmit signal power would be 37dBm (= 5 W) [11]. Three healthy subjects (2 male, 1 female) volunteered to participate in this study. The characteristics of the chosen subjects are: 24 to 29 years old, 150 to 175 cm height and 50 to 78 Kg weight. The sweep signal frequency range is from 300 KHz to 200 MHz with a 50 Ω impedance network analyzer.

In the first experiment, the receiver electrodes was attached on the subject's left forearm and the transmitter electrodes was positioned on the upper left arm. The distance between the centers of the electrodes was set to 15 cm. This was repeated with both transmitter and receivers on the forearm (no joint). In the next experiment, the subject was asked to stand and extend the lower arm for joint angles of θ = 45, 90, 135, and 180 degrees respectively. At each position, the attenuation was measured for the frequency range 300 KHz to 200 MHz. The measurements for each position were repeated three times and the average was taken and reported. In the last experiment, the inter-electrode distance was then increased to 20 cm and the arm was moved as before.

III. RESULTS

A. Influence of Joint-Segment

The curves in Figure 3 depict the sample characteristic of subject 2. The graph shows that most of the attenuations (signal power received or S21) in presence of a joint were on average 4.15 dB higher than when there was no joint between transmitter and receiver. This difference was more prominent in the frequency range of 60 MHz to 170 MHz.

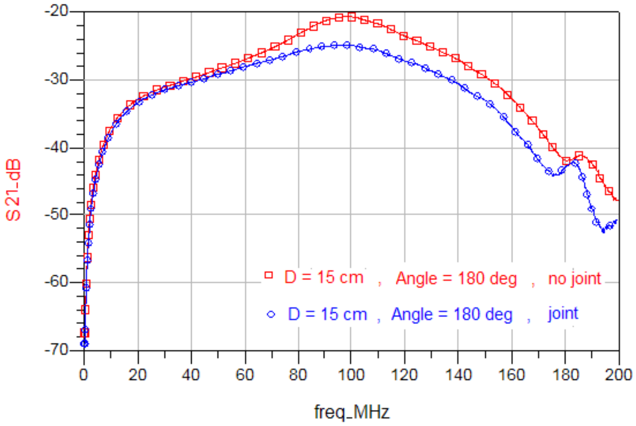


Fig. 3. Effect of joint-segment of subject's left arm.

B. Effect of Joint Angle

The attenuation measured for different angles and distances between transmitter and receiver is shown in figure 4a and 4b. The measurement result of left hand experiments (when the distance between transmitter and receiver was 15 cm and 20 cm and the joint angle was 45°) shows that the attenuation decreased gradually until about 87.70 MHz and 98.20 MHz respectively with increase in frequency. Beyond this point there is a sharp increase in attenuation till 162 MHz and 177 MHz. It can be observed that the minimum attenuation is 23.09 dB in 86.10 MHz when the joint angle is 45 degree and distance between transmitter and receiver is 20 cm. The maximum attenuation was observed when the arm was horizontally straight (180°).

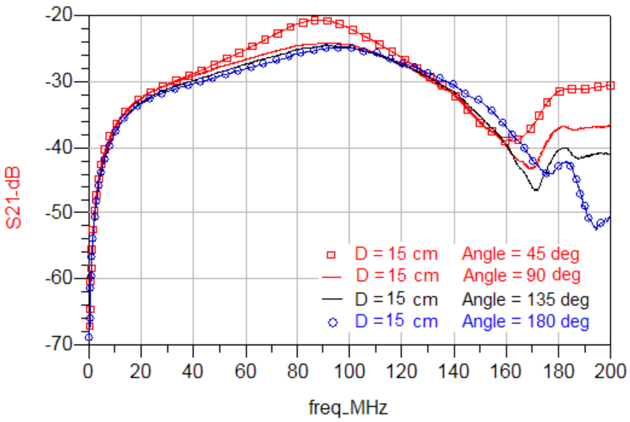


Fig. 4a. Variation of S_{21} parameters against input signal frequencies 0.3-200 MHz. The receiver and transmitter are attached to lower and upper left arm 15 cm apart.

Figure 5 also shows the signal attenuation for all subjects in the same situation. The minimum attenuations are 21.1 dB, 24.6 dB, and 24.13 dB for subject 1 (29 years old male), subject 2 (26 years old male), and subject 3 (female) respectively. The minimum attenuation for all three subjects lay within the frequency range of 70 MHz to 94 MHz.

IV. DISCUSSION

The whole body motions comprise continual movement of body limbs such as bending or stretching. Hence, body movements can be described more precisely as continual joint motions that lead to limb movements. In this work, we have investigated the effect of joint segments on signal attenuation in the capacitive coupling mode of IBC. Below 40 MHz the results show less than 1 dB variation in attenuation between different limb positions. This is due to the fixed distances between transmitter and receiver electrodes on the human body. For frequencies above 40

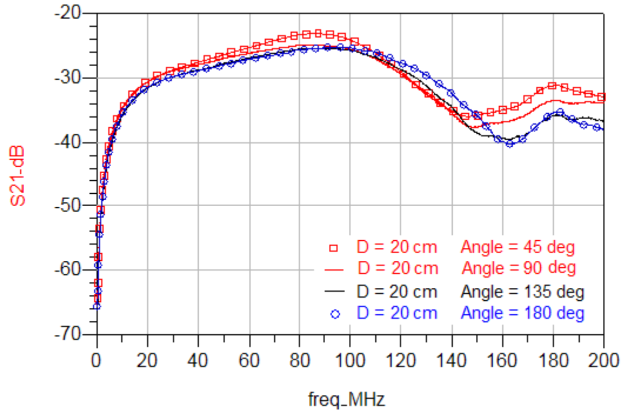


Fig. 4b. Variation of S_{21} parameters against input signal frequencies 0.3-200 MHz. The receiver and transmitter are attached to lower and upper left arm 20 cm apart.

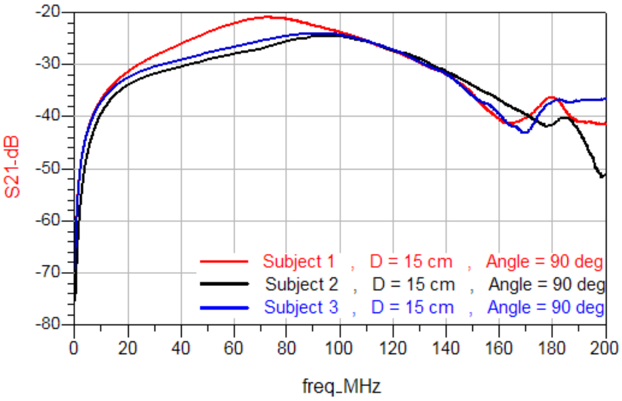


Fig. 5. Signal attenuation of all subjects in same conditions.

MHz, the maximum difference of attenuation was found to be 4.55 dB between joint angles of 45 and 180 degrees. It was found that attenuation increased as the joint angle increased. For example, the attenuation was 20.639 dB, 24.245 dB, 24.711 dB, and 25.186 dB for 45, 90, 135, and 180 degrees respectively for the frequency of 87.70 MHz as a point with minimum attenuation (figure 4a). This could be due to the transmitter and receiver electrodes being physically closer together through the air (e.g. 5.8 cm for 45 degree) when the joint angle is smaller, and in this frequency range the near field effect becomes a stronger return path giving rise to lower attenuation.

We can divide the attenuation curves (Figure 4a and 4b) into four different regions according to frequency; 300 KHz to 40 MHz where we observed that attenuation decreased at an approximately linear rate and was less affected by joint angles. This could be due to a majority of the signal power traversing the limb segment but at increasing penetration depth with frequency. The second area comprises the minimum of attenuation which lies in the frequency range of 40 MHz to 100 MHz for different positions. This region could signify maximum penetration depth and hence joint effects (sudden changes in dielectric properties) are the most visible. The next area starts from 100 MHz to 165 MHz in which the attenuation increases sharply at a linear rate as high frequency starts to give rise to skin effects. In the last frequency range from 165 MHz to 200 MHz and above, variations do not follow a constant behavior potentially due to electromagnetic propagation. Different resonant frequencies (dependent on the limb characteristic) would explain the decrease in attenuation at interval frequency ranges. The results appear to generalize similarly across the three subjects tested.

The variation of attenuation is due to flow of current through different tissue layers possessing differing dielectric properties. Since muscle has very high salinity as well as high water content, a good conductivity (0.701 S/m at 87 MHz with minimum attenuation) is expected for muscle. Joint-segments do not contain a large mass of muscle and they are protected by cartilage which has even lower conductivity compared to muscle (0.467 S/m at 87 MHz) [12]. This could explain why the presence of a joint between transmitter and receiver increases the signal attenuation between two limbs by approximately 4.15 dB for transmission frequencies between 40-100 MHz. Based on Figure 5, it can be seen that the 'sweet spot' (minimum attenuation) in the presence of a joint would be in the 60-100 MHz region for capacitive coupling. Future work will look at developing circuit models for describing the observed empirical results. These developments will improve the efficacy of the capacitive technique as an IBC method for healthcare monitoring systems. The technology will increase patient convenience and improve the cost effectiveness of care.

V. CONCLUSION

IBC is a novel data communication technique using the human body itself as the transmission medium or channel. The present study focused on signal attenuation in IBC systems due to limb position effects. We studied the joint-segment effect and influence of joint angle on subject's left arm. Based on three subjects, it was concluded that the increase in attenuation was proportional to the angle between the forearm and upper arm. It was also found that the presence of a joint increased the attenuation by an approximately constant amount.

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