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Hand Palm Local Channel Characterization for Millimeter-Wave Body-Centric Applications

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ABSTRACT The body-centric wireless channel characterization mostly utilizes whole body models. However, localized channels for body parts consistently interacting with the wireless device have their own importance. This paper attempts to characterize the hand palm local channel through experimental measurements at three millimeter-wave frequency bands of 27-28 GHz, 29-30 GHz, and 31-32 GHz. Five human subjects are used in this study. Net body loss is found to be 3dB for different subjects with subject-specific and varying palm shape size is found to be the primary affecting source. The repeatability of the on-body propagation measurements is found to be within 10% of variance.

INDEX TERMS Body-centric channel, hand palm, on-body propagation, subject-specific.

I. INTRODUCTION

Development of wireless technologies accompanied by continuous device miniaturization has made wearable micro processing systems a reality of our daily life [1], [2]. Body-centric communications are therefore, anticipated as one of the major application areas of modern electronics. Wireless channel characterization with efficient performance antenna serves as a fundamental element in communications system deployment [3]. A mathematical model of in-vivo wireless signals in ultra-wideband (greater than 7 GHz) is proposed in [4]. Good channel model parameters can effectively save engineering practice time and cost, and can better enhance the actual system link design. For instance, a respiratory rhythm sensing platform based on channel parameters is implemented in [5].

Generally, the radio wave propagation between the base station and the mobile terminal is considered relatively stable [6]. However, inclusion of a human user at the receiving end in Body-centric Networks (BCNs) makes this channel highly unstable and erratic due to electromagnetic absorptions/scattering from the body surface, continuous body movements and posture changes. On-body channel characterization using whole body has therefore been a popular research topic for the last couple of years [7]. These studies have considered effects of on-body terminal location, physical aspects of the user and geometry of the surrounding environment. It is a well-established phenomenon that changes in these factors affects the antenna impedance matching and radiation characteristics resulting in a deteriorated channel quality. Experiments have shown that the path loss due to different on-body antenna positions and varying body postures is as high as 50 dB, indicating that even at lower frequencies, the sensitivity is theoretically not high, and the change interval is already significant [6]. It is argued that because the multipath signals and unpredictable posture changes, development of a single universally accepted communication channel model is theoretically impossible. Focus on subject specific localized channels could rather be beneficial in such scenarios as whole body channel modeling introduces large range of different variables.

In [8], the researchers have used two inhomogeneous male and female digital human phantoms to accomplish channel characterization and link budget estimation for wireless

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implants operating at Medical Implanted Communication Services (MICS) and Industrial, Scientific, and Medical (ISM) bands. The radiation performance of the antenna is found to be highly correlated with implant location and body mass index highlighting the need of localized channel characterization. Electromagnetic near-field absorption of biological tissues is also characterized at 418 MHz and 916.5 MHz in [9] and at 30 MHz to 6 GHz in [10]. A subject-specific radio channel characterization for wearable body-centric medical applications operating at 3-10 GHz is performed in [11]. The authors have concluded that wireless channel have an intrinsic relationship with gender, posture and height of the human subject as these traits dictate 1/5th of the total observed path loss. It is therefore, pertinent to investigate and accommodate user related factors to achieve energy-efficient and reliable body-centric wireless links.

In [12], the authors have studied helical sweat tubes widely distributed in human skin and filled with conductive aqueous solutions from the perspective of optical coherence tomography. Results in the mm/sub millimeter wave (mmWave) bands show that human skin has its own role as a low-Q helix antenna. The spectral response in the mmWave region is determined by the activation level of the perspiration system. It is also related to the heart rate and the physiological pressure manifested by systolic blood pressure. The authors in [13] have explored the surface wave propagation at mmWave frequencies concluding that in order to construct a possible generalized path loss model that can provide accurate link budget assessment for different users, a thorough investigation of path loss changes in body parts and shapes are necessary at mmWave frequencies.

In [14], the researchers have investigated the propagation mechanism of electromagnetic waves through the tissue, derived an optimized frequency range, and obtained the maximum achievable efficiency of radiation energy transfer from the body to the free space. At the same time, it is pointed out that the interference introduced by the surface wave is very significant, and the optimized device can achieve a quantitative improvement in efficiency compared with existing devices. It also shows that the study of hand channel characteristics closely related to daily operations can directly promote significant improvements in body centric application performance.

An analogy-related work in [15] introduces detachable radiation elements antenna design concept that provide modular geometric reconstruction for wearable applications. It is easy to understand that the hand channel characteristics closely related to the operation buttons have undoubtedly facilitated the wide application of such antenna design concepts. In [16], high-resolution palm-print recognition is used for user authentication. It is observed that surface lines of the human palm are subject specific and have varying effect on the radio channel generating unique signatures. Subject-specific on-body channel considering a male human user and high gain 4.5 GHz antenna and using a narrow-band real-time channel sounder is evaluated in [17]. In [18], an S-band multi-polarized reconfigurable antenna is proposed for biomedical applications.

These studies highlight the importance of wireless channel characterization for an optimized body-centric application and show the importance of studies into local channel attributes. Millimeter wave frequencies are gaining interest for next generation body-centric communications due to inherent benefits of high data rate, shorter wavelength, wider bandwidth and device miniaturization. Higher free-space attenuation is another feature of mmWaves that limits interference while less penetration depth in biological tissues helps to reduce potential health hazards [19]. Though well studied at lower frequencies, local channel characterization at mmWave frequencies needs further exploration. As the human hands are particularly involved in the operation of wireless devices, their motion (Such as picking up or gripping the device), shape and size can affect the channel more drastically as compared to other body parts. There have been reliable studies to develop channel models between different body parts, but due to the complexity of human motion, local channel models, especially single body parts, body-centric communication modeling are still rare. This letter is an attempt to further the understanding in this important direction by exploring the characteristics of localized channel involving human upper limb and more specifically, the hand palm. The result of the hand palm body centric channel changes, from a certain point of view, similar to the building block module, will help handheld application developers to clarify the local channel changes in the palm of the millimeter wave band. Different from the existing more comprehensive multiple local channel characterization. Five human subjects of varying body physique, age and gender are employed to gather the localized channel data at three mmWave frequency bands of 27-28 GHz, 29-30 GHz, and 31-32 GHz.

Following the introduction in this section, rest of the letter is organized in three sections. Section II describes measurement set-up, Section III presents analysis of the results and Section IV draws conclusion.

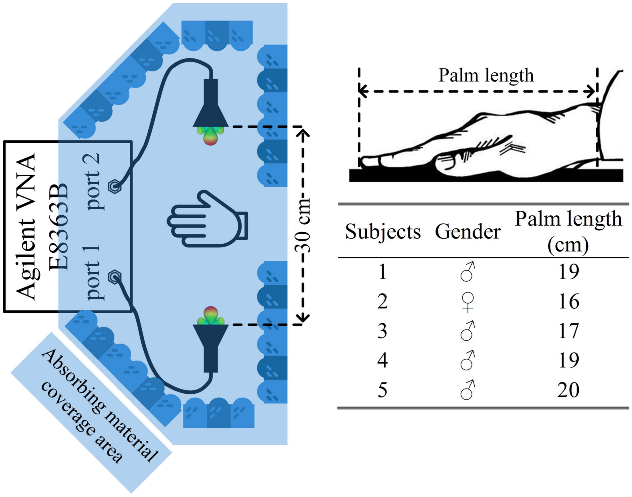
II. MEASUREMENT SET-UP

Channel characteristics in the BCNs depends largely on the extent of distance from the user's body, body posture and on-body antenna position. Organs that are directly interacting with the wireless device, particularly hands, naturally affect its performance more. Modeling and characterization of localized channel and understanding of the fading changes in the palm can therefore, bring large improvements in the design and deployment of a body-centric device.

Wireless channel modeling in BCNs is based on the theoretical analysis of creeping wave propagation [20]. In this study, the channel model is derived using diffraction theory, which describes the attenuation of creeping waves along a circular path on the surface of a lossy medium [20]. Monopole antennas are considered to be a suitable choice for BCN applications but suffer from planar structure and large height.

We have therefore used standard horn antennas to prove the idea in this study.

Experimental assessment of antenna gain in body-centric scenario is a difficult task and requires utmost care. If research uses real human subjects, repeatability is not easy to obtain. Some published studies on the full-size human BCNs channel model only give statistical models. This is also the consideration of simultaneous channel characterization of full-size human bodies or multiple human body parts. There are many factors that may affect the radio wave propagation, causes the factors that are really concerned to be disturbed or even overwhelmed. A relatively flexible method is to use human tissue glue. If a phantom filled with tissue fluid is used, the constituent parameters of the shell are not true replication of the human tissue and may change the effectiveness of the results. Therefore, experimental setup as shown in Fig. 1. The microwave absorbing material is placed around the antistatic plane of the experiment to reduce the influence of reflected scattering waves. Agilent's Vector Network Analyzer E8363B is used for data acquisition at three frequency bands of 27-28 GHz, 29-30 GHz, and 31-32 GHz. Frequency step size is kept at 50 MHz. Five human subjects including four male and one female with varying ages and physiques are employed. The standard horn antennas used in the experiment are 30 cm apart and placed at the same height. We define the length of the palm of the subject as the length of the longest finger to the wrist joint when the finger is relaxed and flat. The specific value can be seen in Fig. 1. The given test number is to protect the participants privacy, and the order is the order of participation in the experiment. Measurements at each frequency band are taken thrice to ensure repeatability.



Subjects	Gender	Palm length (cm)
1	♂	19
2	♀	16
3	♂	17
4	♂	19
5	♂	20

FIGURE 1. Hand palm local channel feature collection by five human subjects. On the left, the light blue translucent area is covered by absorbing material. On the right, the definition of the palm length and the participants information are given.

When the receiver is in front of the subject (line of sight condition), direct signal reception is strong and the average path loss for all subjects is almost the same [21]. In the non-line-of-sight case, average change tends to be higher because the received signal mainly contains creeping waves around the human body. These waves are dependent on the size of the human subject and loose energy quickly away from the body surface. These factors have been taken into consideration in the experimental design by placing the subject's palm 30 cm away from the transceiver antennas as shown in Fig. 1. The antenna spacing is determined by considering the common use environment. The size of the handheld device, such as the Surface Book, is about 30 cm in length. In fact, it is already a heavy chunk in the handheld terminal. The radiation pattern of the horn antennas used in the study is illustrated in Fig. 2, a commercial standard gain antenna, which can effectively cover the test area.

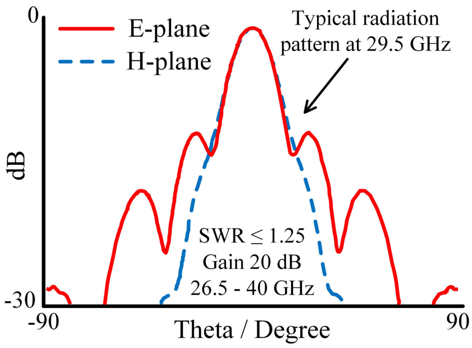


FIGURE 2. The standard horn antenna pattern used in the experiment (free space).

The antenna is ordered for the series of mmWave experiments. From HengDa Microwave Co., the model is HD-320SGAH20. The upper limit of the operating frequency of this type of horn antenna is exactly the upper limit of the measurable frequency of VNA (E8363B). The pattern shown in Fig. 2 is the actual acquisition of the local channel representation for this palm, at 29.5 GHz. Wavelength is equal to 11.1 mm at 27 GHz, 10.3 mm at 29 GHz, and 9.7 mm at 31 GHz, making the hand palm can be treated as an electrically large object.

III. RESULTS AND ANALYSIS

The localized hand palm channel for the five test subjects at multiple frequency bands is quantified. Path loss (S21) measurements for each subject at the three bands are repeated twenty times (Tests 1-3) to ensure repeatability and enhance accuracy. Probability density function is then used to obtain the data distribution for the localized palm channel as shown in Fig. 3. Overall, from the first row of legends, the S21 linear fit is completely in accordance with the size of the subject's hand. That is to say, the change in the area of the hand occlusion does affect the local channel change in the palm. It further supports the complexity of the human body's local channel, especially the hand channel that directly interacts with the communication device. It also means that the simple posture change will have obvious channel changes that can be measured by the instrument.

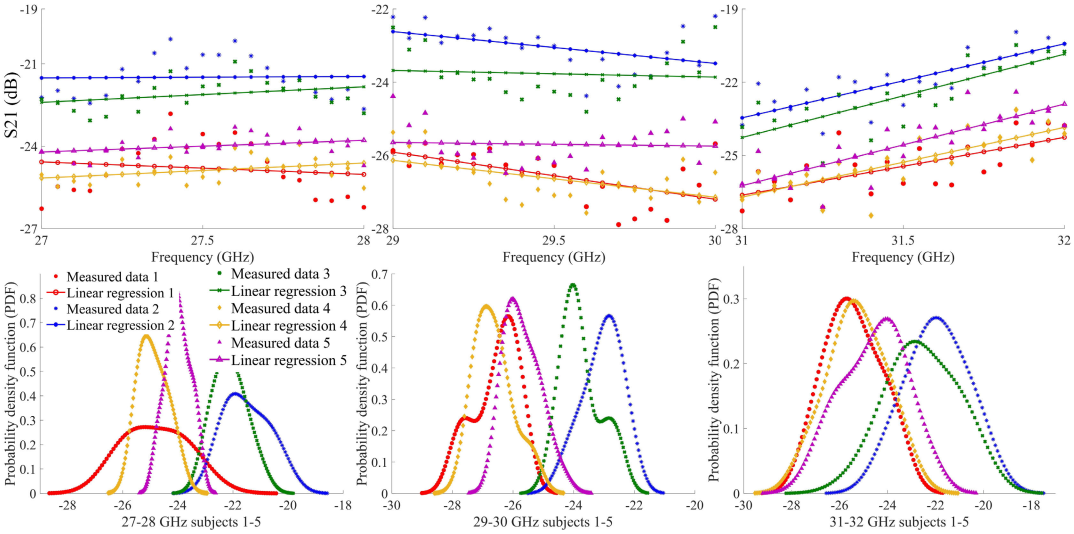


FIGURE 3. The average data collected from five subjects in three frequency bands.

It can be seen from the fitting results in the upper part of Fig. 3, the data for subject 1 and 4 is highly correlated with similar pdf (E.g., the correlation coefficient is about 0.83 at 31 GHz). It is due to the fact that palm length for the two subjects is the same as 19 cm. Curves for subject 2 and 3 are in the same area, means that S21 energy is on the same level, and the mean fitting line is related (E.g., the correlation coefficient is about 0.98 at 31 GHz). Again, lengths of the palms for these subjects are similar (16 cm, 17 cm). Though, subject 5 has the longest palm length of 20 cm, its attenuation is not the largest, which is due to the gain of creeping waves. In the highest frequency band (31-32 GHz), the difference between the path losses for different subjects is significantly smaller, and the correlation of the mean fitted lines is better. All of the pdfs are peaking at around 0.3 and there is no obvious enrichment as compared to the two lower frequency bands where most of the data has shown a high enrichment core fading value of about 0.7.

These results mean that as the signal frequency increases, the local channel characteristics of the palm will become more random. Although the path loss value is not significantly improved, S21 varies from -27 dB to -20 dB at 31-32 GHz. This is because the distance of the measuring antenna is fixed, and on the other hand, because high-frequency radio waves are difficult to transmit to human tissues, it can only interact with the body surface. It can also be seen that when the frequency is increased to about 31 GHZ, the correlation between the S21 fitting data and the frequency is enhanced, indicating that the local palm factor has a reduced influence on the wave propagation. In addition, the high-frequency signal offers better safety for the human user making it more suitable for future body-centric applications.

Net body loss (η) can be defined as the ratio between measured ($P_{measured}$) and theoretical path losses ($P_{theoretical}$):

$$\eta = \frac{P_{measured}}{P_{theoretical}} \tag{1}$$

We have used a statistics variation coefficient (C_v) as a normalized measure of the degree of dispersion. It is dimensionless and is defined as the ratio of the standard deviation (σ) to the mean (μ) as follows:

$$C_v = \frac{\sigma}{\mu} \tag{2}$$

This parameter is a good measure of variation for horizontal contrasts where the average of the characteristics of multiple channels is inconsistent. The C_v is a normalized measure of the degree of dispersion of the data to be characterized. The larger the value of the variable, the greater the degree of dispersion of the data to be characterized, and vice versa means good repeatability.

Table 1 summarizes values of experimentally measured statistical parameters. It can be seen that in a single frequency band. Reflected by η, path loss variation is up to 3 dB for different human subjects. It indicates that the characteristics of localized palm channel are significantly different for different subjects making it a subject-specific channel. A small C_v of less than 10% shows reliability and accuracy of the collected information and quantitative analysis. More specifically, in the lower frequency band, the C_v of multiple subjects is less than 5%. Only when reaching 31 GHz, the discrete attributes of the subjects are only about 5%. The trends and observations are in-line with previous studies done at 5.8 GHz [22], [23].

These results infer that the lossy hand tissues affect the electromagnetic wave propagation in human hand, and this localized channel is highly subject-specific with a high degree of isolation between different subjects. Stronger channel selectivity can be observed at lower frequencies, which we believe is due to better random characteristics in higher frequency bands. The data in Fig. 3, shows that the linear fitting can express well the path loss variations with body shape parameters. This channel can be modeled using pathloss

TABLE 1. Net body loss and variation coefficient values for hand palm local channel at MmWave frequencies.

	Test 1-3 η(dB), C_v(%)		
27-28 GHz Subjects 1-5	-24.9, 4.1	-24.8, 4.3	-24.9, 4.3
	-28.1, 3.8	-28.2, 3.6	-28.2, 3.5
	-27.6, 2.8	-27.6, 2.7	-27.6, 2.5
	-25, 2.2	-24.8, 2.1	-24.6, 2.4
	-25.8, 1.8	-25.6, 1.9	-25.7, 2.2
29-30 GHz Subjects 1-5	-23.9, 2.9	-23.8, 2.9	-23.6, 2.7
	-27.2, 2.5	-27.3, 3	-27.3, 2.8
	-26.6, 2.6	-26.5, 2.9	-26.5, 3.2
	-23.8, 3	-23.7, 2.2	-23.5, 2.5
	-24.8, 2.6	-24.5, 2.3	-24.6, 2.1
31-32 GHz Subjects 1-5	-25.4, 4.7	-25.5, 4.8	-25.4, 4.3
	-28.9, 5.3	-28.9, 5	-29, 6.2
	-28.3, 6.1	-28.3, 6.1	-28.4, 5.9
	-25.7, 4.6	-25.7, 5	-25.4, 4.9
	-26.5, 5.9	-26.2, 5.3	-26.2, 5.4

exponent and shadowing factor as follows [13]:

$$PL(d) = PL(d_0) + 10\gamma \log\left(\frac{d}{d_0}\right) + N(0, \sigma) \tag{3}$$

where $PL(d_0)$ is the estimated path loss, γ is the path loss exponent and $N(0, \sigma)$ is the shadowing factor. Table 2 gives results for this model.

TABLE 2. Pathloss exponent and shadowing factor for hand palm local channel.

	Test 1-3 (Pathloss Exponent, Shadowing Factor)		
27-28 GHz Subjects 1-5	-0.39, 1.01	-0.34, 1.08	-0.63, 1.07
	0.16, 0.82	0.02, 0.78	-0.02, 0.74
	0.52, 0.62	0.59, 0.6	0.59, 0.56
	0.82, 0.55	0.46, 0.53	0.37, 0.6
	0.35, 0.43	0.37, 0.45	0.55, 0.52
29-30 GHz Subjects 1-5	-0.76, 0.77	-1.62, 0.78	-1.49, 0.73
	-0.83, 0.59	-0.89, 0.7	-0.89, 0.63
	-0.16, 0.61	-0.37, 0.7	-0.01, 0.76
	-0.65, 0.8	-1.14, 0.58	-1.24, 0.66
	-0.2, 0.65	-0.08, 0.59	-0.03, 0.55
31-32 GHz Subjects 1-5	2.19, 1.19	2.91, 1.21	2, 1.09
	2.94, 1.17	2.61, 1.1	3.56, 1.36
	3.4, 1.37	3.29, 1.37	3.56, 1.33
	2.45, 1.15	3.27, 1.26	2.85, 1.26
	3.49, 1.43	3.39, 1.31	3.16, 1.34

It has been observed that significant path loss occurs due to the presence of electrically large human hand. The channel appears to be highly subject-specific as path loss exponent and shadowing factor varies significantly for the human subjects having similar palm size. Following the general modeling indicators, we give the linear regression coefficient of the measured data as path loss exponent, the standard deviation of the data as the shadowing factor. A 50% change in the path loss exponent is noted for the test subjects having a similar palm length of 19 cm. A 30% change in channel statistics is observed for test subjects with similar palm size but opposite gender.

IV. CONCLUSION

Development of ultra-low power wireless sensors for wearable devices and medical implants requires subject-specific studies and channel models to understand the local wave propagation. Subject-specific studies based on whole human body are not only complex and time consuming but also sometimes uncalled-for as the human organs directly in contact with the wireless device are the prime affecting factor. Localized channel characterization is therefore a necessity. Scarcity of such studies at recently popular mmWave frequencies further adds to the need of such studies.

A localized hand palm channel model for mmWave frequencies has been proposed. The model is based on propagation measurements using two horn antennas and five human subjects with varying palm lengths. The experimental results have shown that, in the same frequency band, the path loss variation is as high as 3 dB due to varying subject gender and palm sizes. It makes this channel highly subject-specific. This understanding will be further strengthened by employing multi-band antennas and wider variety of human subjects. It will serve as an important guideline for the antenna designers to achieve higher reliability and efficiency out of body-centric communication systems.

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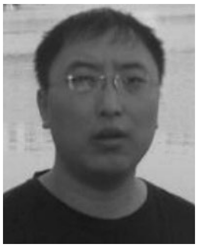

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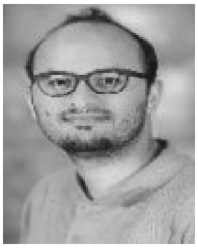

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