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User body effects on mobile antennas and wireless systems of 5G communication

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Abstract—User body effects on mobile antennas and wireless systems for the fifth-generation (5G) mobile network are analyzed in this paper. Effects on different antenna technologies in mobile handsets include single antenna systems, multiple antenna systems, and the antenna arrays are discussed with simulations and measurements. The corresponding impacts on wireless networks are studied as well with raytracing simulations. Several technologies on mitigating user body effects have also been provided.

Index Terms—user body, 5G, mobile, antenna, antenna array, millimeter wave, MIMO.

I. INTRODUCTION

An antenna system design for the mobile handset application is a critical and complicated task, where multiple parameters, such as the impedance bandwidth and the antenna efficiency, need to be optimized simultaneously. Among all the challenges that antenna designers need to face, evaluating and mitigating user body effects is an unavoidable work since mobile antennas usually operate very close to the user body.

In general, a user affects the performance of the antenna system negatively, which can eventually cause a link-level failure of a wireless system. Therefore, the evaluation of user body effects become necessary. Currently, a set of standard tests and body phantoms have been widely utilized for measuring a mobile handset radio frequency (RF) performance with user body impacts in the spectrum below 6 GHz, e.g., the data mode and the talk mode in CTIA over the air test (OTA) plan [1]. Studies on mitigating user body effects in this spectrum has also been carried out intensively [2]-[10].

However, effects from a user body are not constant over frequency bands. This is critical for the 5G network, which aims to utilize the spectrum not only below 7 GHz but also into millimeter wave (mmWave) frequencies [11]. Studies on measuring the user body effect on mmWave mobile antennas have been emerged in recent years [12]-[18]. Overall, understanding user body effects cross a much wider frequency range becomes a critical task for the time of 5G.

In this paper, we primarily focus on providing a thorough survey and study on user body effects cross major 5G cellular bands. The analyses are carried out with some key RF parameters that can provide an intuitive view of how the body effect impact on the wireless network. In

addition, technologies on mitigating user body effects at different frequency ranges will also be presented.

II. USER BODY EFFECT ON CELLULAR ANTENNA SYSTEM IN FREQUENCY RANG I

A. Single antenna system

Comparing to LTE networks where most of the spectrums are located below 3 GHz, the frequency range (FR) between 410 MHz to 7125 MHz has been defined as FR1 in 3GPP specifications for 5G communication [11]. Similar to earlier generations of mobile networks, user body effects on a single antenna system can be concluded as the antenna mismatch loss and the power absorption loss (see Fig. 1). The former effect de-tunes the antenna impedance matching, and the later one degrades the radiation efficiency of the antenna. Consequently, the total efficiency related RF parameter, e.g., total radiated power (TRP) and total isotropic sensitivity (TIS), are decreased. Measurements on TRP and TIS of some commercial phones have been reported in [6], which indicates the loss in TRP can be more than 15 dB due to body phantoms.

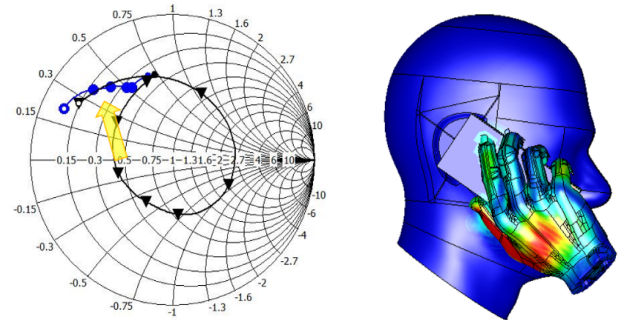


Fig. 1. The illustration of the user body effect on the antenna impedance matching (left) and the power absorption (right).

B. Multiple antenna system with antenna diversity

Antenna switching [19] and combining [20] (also known as antenna diversity) are typical methods to improve RF performance, especially for the reception performance of mobile phones nowadays. This is contributed by the fact that multiple antenna systems have been popularly implemented. In Table I, the total TIS of a mobile handset prototype with

multiple antennas in free space and besides head and hand (BHH) are listed, the total TIS is obtained based on a maximum ratio combine (MRC). It can be observed that almost 3 dB TIS can be improved by double the number of reception antennas.

Designing the mobile antenna to be inherently robust to user body effects is also helpful. This is particularly critical for the antenna designs using the metal frame of the mobile phones since they are usually touched directly by the user's hands. A couple of examples are shown in [21]-[22].

TABLE I. MEASURED TIS OF A MOBILE HANDSET WITH MULTIPLE ANTENNA SYSTEM

Number of antennas	TIS in free space (dBm)	TIS in BHH (dBm)
2	-97.3	-90.8
4	-100.4	-93.1

C. Multiple antenna system with spatial multiplexing

The antenna diversity technologies mentioned above are usually used to enhance the signal to noise (SNR) ratio of the wireless system. As an alternative, using multiple antennas with parallel data streams (spatial multiplexing or multiple-input multiple-output (MIMO)) to increase the channel throughput has also been deployed in LTE networks and further expended in 5G NR networks. User body effects on MIMO performances have been investigated in recent years [8]-[10]. The MIMO performance of a mobile handset is usually evaluated by the channel throughput. Currently, the test setup of MIMO performance for 5G new radio (NR) in 3GPP is still under discussion [23]. Nevertheless, similar to the LTE test setup, the channel throughput is going to be measured over an emulated channel model. However, such a test is less intuitive for antenna engineers to optimize the MIMO antenna, especially when the handset is beside a body phantom. In [24], the parameter multiplex efficiency (MUX) has been defined, which can indicate the performance of a MIMO antenna system under a rich scattering environment:

$$\eta_{MUX} = \frac{1}{\sqrt{\left(\prod_{i=1}^M \eta_i\right) + \det(R)}} \quad (1)$$

Where η_i stands for the total efficiency of the i th antenna, and R denotes the antenna correlation matrix. The MUX offers a direct link from antenna parameters to the MIMO channel capacity, and we can easily observe how the user body affects the MIMO performance. As an example, the MUX of a two-port MIMO antenna design for a mobile handset in free space and with a hand phantom is shown in Fig. 2. It can be observed that the MUX dropped dramatically when the user's hand is presented, and the major contributor to the losses comes from the total efficiency loss of the antennas.

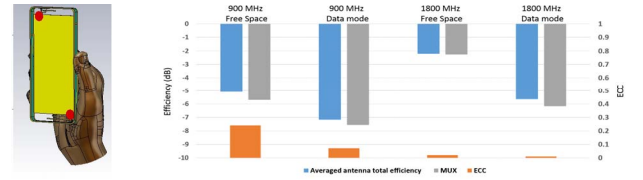


Fig. 2. The simulation model in the data mode, and the MIMO antenna performance variation due to the hand effect.

III. USER BODY EFFECT ON CELLULAR ANTENNA SYSTEM IN FREQUENCY RANG 2

The previous section focuses on user body effects in FR1 of 5G NR, which is similar to body effects in previous 4G, 3G, and even 2G mobile networks due to the closely located frequency bands. However, jumping into the FR2 of 5G NR, it needs a thorough study to understand how a user body interacts with the antenna and communication system at such a high spectrum. So far, four FR2 bands have been defined in 3GPP NR specification [11], which is shown in Table II. A new band n259 is also under discussion up to date.

TABLE II. NR OPERATING BANDS IN FR2

Operating band	Frequency
n257	26500 MHz - 29500 MHz
n258	24250 MHz - 27500 MHz
n259	39500 MHz - 43500 MHz
n260	37000 MHz - 40000 MHz
n261	27500 MHz - 28350 MHz

In FR1, the user distorts the near field of antennas and leads to a changing of antenna impedance. Besides, the large amount of electromagnetic energy penetrates the body and be absorbed. However, due to the much shorter wavelength and less penetration depth in FR2, the mismatching loss and absorption loss has been dramatically reduced [25]-[27]. On the other hand, the shadowing loss or the blockage caused by the user body has become the dominant effect [12]-[14].

The shadowing effect is rarely mentioned in the FR1 since the propagation channel is assumed to be richly scattered: incoming signals arrive at the mobile handset from multiple directions, and thus the direction of the radiation becomes less critical. However, the channel is more dispersive in terms of multipath components in FR2 due to the propagation environment as well as the utilizing of beamforming on both base station (BS) and user equipment (UE). Therefore, the spherical coverage of a mobile handset becomes the most fundamental RF requirement since the antenna system in UE, especially the mobile handset, needs to be able to receive signals from an arbitrary direction. Currently, 3GPP has defined the requirement on the spherical coverage of FR2 UE in free space for transmission and reception, which are measured by the cumulative distribution function (CDF) of the equivalent isotropically radiated power (EIRP) and the effective isotropic sensitivity (EIS) over the sphere, respectively.

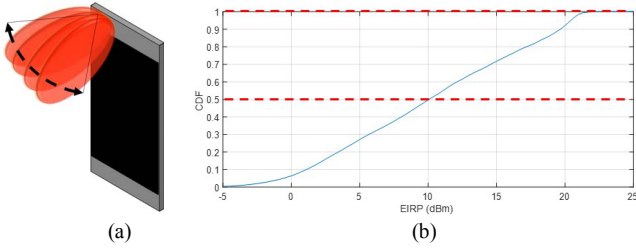


Fig. 3. (a) The illustration of mobile handset spherical coverage with beamforming array. (b) The illustration of CDF of EIRP for a mobile handset.

An illustration of the spherical coverage of a handheld mobile device with beam steering capability is shown in Fig. 3(a), and the CDF of EIRP is shown in Fig. 3(b). The mobile handset is categorized as power class (PC) 3 UE in 3GPP, where the uplink spherical coverage requirement in FR2 is listed in Table II.

TABLE III. UE MINIMUM PEAK EIRP AND SPHERICAL COVERAGE FOR POWER CLASS 3 (FREE SPACE)

Operating band	Min peak EIRP (dBm)	Min EIRP at 50 %-tile CDF (dBm)
n257	22.4	11.5
n258	22.4	11.5
n259	18.7	5.8
n260	20.6	8
n261	22.4	11.5

Though the 3GPP requirement only applies to the free space scenario, the shadowing loss from the user body place a degradation on the spherical coverage and impact on the real-life performance of 5G mobile handset. Therefore, a good understanding of the UE spherical coverage degradation due to the user body effect in FR2 is necessary.

A. Shadowing loss due to the hand effect:

The hand can block the antenna radiation when the finger or the palm placed upon the antenna elements. A simulation model of a device with a smartphone form factor with a hand phantom at 28 GHz is shown in Fig. 4(a), where two linear arrays are placed in the device. The antenna array 2 is blocked by the index finger of the hand phantom, and therefore, its spherical coverage is degraded by about 5 dB at CDF = 50%. Meanwhile, the array 1 that on top of the device is barely impacted by the hand phantom, and it can reach a similar spherical coverage performance comparing the free space performance. This analysis shows that the shadowing loss due to the hand effect can be effectively mitigated by switching between multiple arrays.

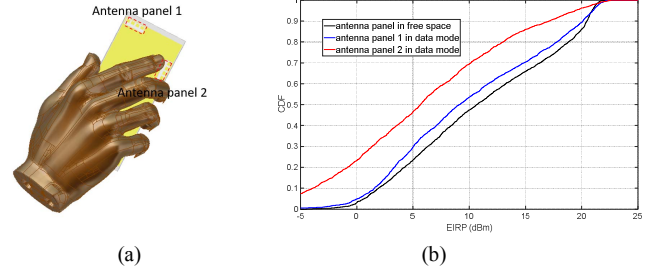
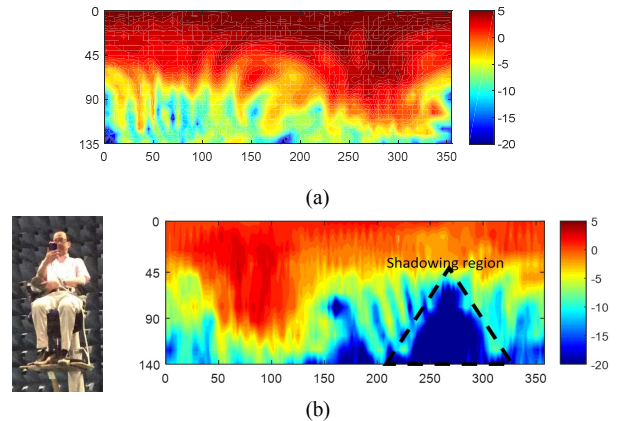


Fig. 4. (a) The simulated model of a mobile handset with a hand phantom. (b) The simulated CDF of EIRP for the mobile handset at 28 GHz.

B. Shadowing loss due to the torso and head effect:

The torso effect is rarely considered when we discuss the user body effect in FR1. However, its shadowing impact is unneglectable in FR2 due to its large physical dimension, which can be observed from the real user blockage measurement at 28 GHz (see Fig. 5): The far-field radiation patterns of a single antenna element is measured in three use cases (free space, data mode, and talk mode) with a real user: The antenna element is placed on the top of the device and is not touched by the user's hands; therefore, the hand effect can be excluded based on our analysis in the previous section. Even though a clear user body shaped shadowing region can be observed in the data mode, and the shadowing loss is about 25-30 dB within the shadowing region. The CDF of EIRP has also been plotted in Fig. 6: About 2 dB, 5 dB and 10 dB degradation can be observed at CDF = 100%, 50% and 10 %, respectively. In the talk mode, since the antenna is very closed to the user's head, it can be observed that the user's head has strongly shaped the radiation pattern of the antenna element.

Analysis in [13], [28] shows different element has similar spherical coverage performance in data and talk mode with real users, which indicates that designing element differently for antenna array can not resolve the body shadowing issue effectively. In [29], the body shadowing area can be reduced by combining multiple arrays that are placed around the four corners of the mobile handset.



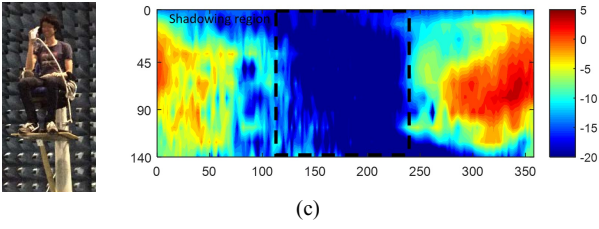


Fig. 5. Measured far-field radiation pattern of an antenna at 28 GHz in (a) free space, in (b) the data mode, and in (c) the talk mode.

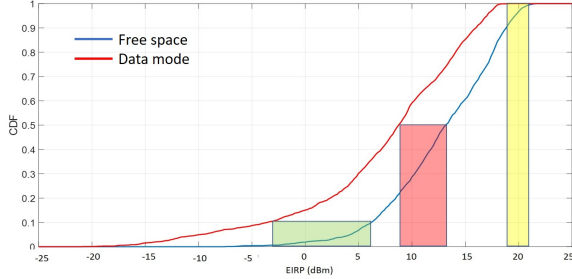


Fig. 6. The CDF of EIRP in data mode with a real user.

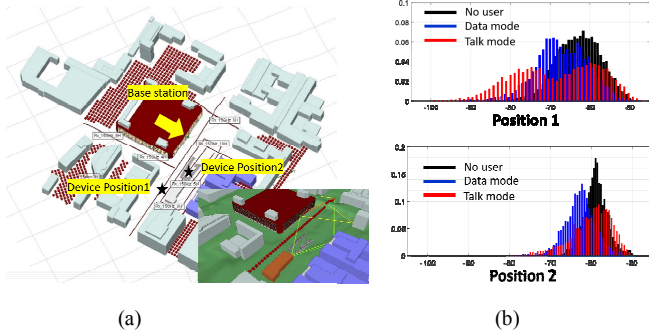


Fig. 7. (a) The 3D raytracing simulation model at 28 GHz and (b) the RSS PDF of the mobile handset at device position 1 and position 2 with the rotated orientation.

Different with the efficiency loss in FR1, the shadowing effect from a user in FR2 is a directional dependent loss, and thus its impact on a cellular network also depends on the spatial parameters of the wireless channel, e.g., angle of arrival (AoA) and angle of depart (AoD) of the downlink signals. To exam the user body effect on a 5G mmWave wireless link, a 3D raytracing simulation has been carried out at 28 GHz in an urban environment, where multiple buildings with 8-10 m are included (see Fig. 7(a)). The detail of the simulation model can be found in [27].

The probability density function (PDF) of the received signal strength (RSS) of a mobile handset with and without a user is shown in Fig. 7(b). The RSS is simulated at two positions in the environment with the device/user randomly orientated over the horizontal plane. In position 1, the incoming signal is limited to a few directions with a small angle spread (AS) due to the urban canyon effect. As can be observed, the mean value of the RSS does not change

dramatically with different use cases, but the standard deviation has been increased with a broader shadowing region. This behavior is substantially different from user body effect in FR1, and it implies that a considerable uncertainty of the cellular network performance can be expected in the FR2 network, especially if signals of the base station can only come from a single direction.

In contrast, the AS of the incoming signal distributed more uniformly over the horizontal plane when the device is placed in position 2: Several cars are around the user, and they create a rich scattering environment. Consequently, it can be observed that the PDF of RSS in all three use cases become comparable, and the standard deviation has been reduced in all use cases. This result indicates a possible mitigation method of the user body effect in FR2 from the network deployment aspect: Multiple BSs or transmission points (TPs) are desired to be deployed over different angles to illumine the covered area in order to create an angular diversity system which could be more robust against the shadowing loss of user body (see Fig. 8).

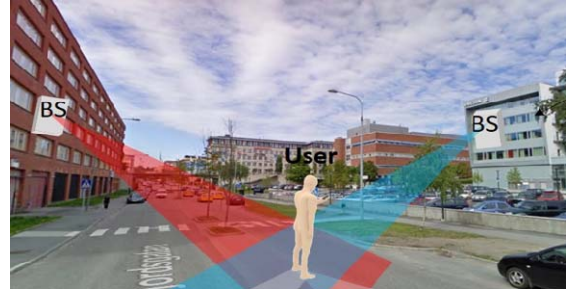


Fig. 8. Deployment multiple BSs to mitigate the user body blockage.

IV. CONCLUSION

User body effects on 5G mobile handsets and cellular systems have been comprehensively discussed in this paper over multiple frequency ranges. It can be found that the effects of the user body are distinct at different frequency ranges. In FR1, the user body effect behaves very similarly to the LTE system, which mainly shows as a loss in the TRP and TRS of a mobile handset. The antenna diversity is the primary solution for mobile handsets to overcome the user body effect. Besides, designing the antenna to be robust to the user body inherently is also a practical way to resolve this issue.

On the other hand, the user body effect mainly shows as a blockage loss to the spherical coverage of antenna arrays in FR2. Though 3GPP has placed the requirement on the spherical coverage of antenna systems in free space, the performance with a user can be different, as shown in this paper. Ray-tracing simulations presented in this work demonstrate that the shadowing loss due to the user body cannot be ignored for the cellular system at such a high frequency. Implementing multiple arrays in mobile handsets and optimizing the network deployment is critical for overcoming the user body effect for the 5G network in FR2.

As future works, user body effects on higher-order MIMO antenna systems in FR1, e.g., 8×8 MIMO, shall be studied, particularly in higher frequencies part of FR1. For FR2 and frequencies beyond, a more in-depth understanding of the user shadowing effect on wireless networks is needed, where real-time measurements on the wireless channel with user body effects can be beneficial. Standard body phantom at mmWave will also be needed for reproducing repeatable and comparable measurement results.

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