Human Exposure to RF Fields in 5G Downlink

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Abstract—While research on communications in millimeter wave (mmW) bands has been focused on performance improvement, their potentially harmful impacts on human health are not as significantly studied. Prior research on radio frequency (RF) fields in mmW cellular communications have been focused on uplink only, due to closer contact with a transmitter to a human body. In this context, this paper claims the necessity of thorough investigation on human exposure to downlink RF fields, as cellular systems deployed in mmW bands will entail (i) deployment of more transmitters due to smaller cell size and (ii) higher concentration of RF energy using a highly directional antenna. In this paper, we present the maximum possible human RF exposure in a downlink of a Fifth-Generation Wireless Systems (5G). Our results show that 5G downlinks can expose human users to higher RF emissions than a current cellular system. This paper also claims that specific absorption rate (SAR) should also be taken into account for determining human RF exposure in mmW downlinks.

Index Terms—5G; mmW; Downlink; Human RF exposure; SAR; PD

I. INTRODUCTION

It is acknowledged that exposure to RF has negative impacts on the human body. The rapid proliferation of mobile telecommunications has occurred amidst controversy over whether the technology poses a risk to human health [1]. At mmW frequencies where forthcoming mobile telecommunications system is likely to operate, two changes that will possibly occur have the potential to increase the concern of exposure to human users in RF fields. First, larger numbers of transmitters will operate. More base stations (BSs) will be deployed due to the proliferation of small cells [2]-[3] and mobile devices accordingly. Second, narrower beams will be used as a solution for the higher attenuation in higher frequency bands [4]-[5]. Very small wavelengths of mmW signals combined with advances in RF circuits enable large numbers of miniaturized antennas. These multiple antenna systems can be used to form very high gains. Such higher concentration of RF energy will increase the potential to more deeply penetrate into a human body. Moreover, one important feature of the future cellular networks is small cell networks. The consequences of this change will be two-fold: (i) APs/BSs will serve smaller geographic areas and thus are located closer to human users; (ii) larger numbers of APs/BSs will be deployed, which will lead to higher chances of human exposure to the RF fields generated by downlinks.

II. RELATED WORK

This paper is motivated by the fact that prior work is not enough to address some possible potential health impacts of the forthcoming 5G technology.

A. Measurement of Human RF Exposure

Being aware of the health hazards due to electromagnetic (EM) emissions in mmW spectrum, international agencies such as the Federal Communications Commission (FCC) [6] or the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [7] set the maximum radiation allowed to be introduced in the human body without causing any health concern. According to [8], FDA and others had stated that research had not shown RF emissions from mobile phones to have adverse health effects, but insufficient information was present to conclude that RF emissions posed no threats. It was also mentioned that some individual studies suggested possible effects of long-term exposure to high RF fields that can impose damage to biological tissues. It indicates that though agencies like WHO or FDA believe that the weight of scientific evidence does not show an association for adverse health outcomes due to RF fields, all these agencies have claimed that additional research is warranted to address any gaps in knowledge. In fact, WHO’s International Agency for Research on Cancer (IARC) has classified RF fields as possibly carcinogenic to humans [22]. Heating due to EM exposure in mmW is absorbed within the first few millimeters (mm) within the human skin; for instance, the heat is absorbed within 0.41 mm for 42.5 GHz [9]. The normal temperature for the skin outer surface is typically around 30 to 35°C. The pain detection threshold temperature for human skin is approximately 43°C as reported [1] and any temperature over that limit can produce long-term injuries.

One problem is that the literature on the impact of cellular communications on human health is not mature enough. Power density (PD) and SAR are the two most common quantities used to measure the intensity and effects of RF exposure [10][11]. However, selection of an appropriate metric evaluating the human RF exposure still remains controversial. The FCC suggests PD as a metric measuring the human exposure to RF fields generated by devices operating at frequencies higher than 6 GHz [6], whereas a recent study suggested that the PD standard is not efficient to determine the health issues especially when devices are operating very close to the human...
body in mmW [12]. Therefore, this paper examines the human RF exposure by using both PD and SAR.

B. Reduction of Human RF Exposure

Very few prior studies in the literature paid attention to human RF exposure in communications systems [11][12][15]. Propagation characteristics at different mmW bands and their thermal effects were investigated for discussion on health effects of RF exposure in mmW radiation [12]. Emission reduction scheme and models for SAR exposure constraints are studied in recent works [13][14]. Note that if the BSs have the power control or adaptive beamforming capability according to [16], the human exposure can be reduced sufficiently. Also, if both mmW and microwave architecture work combined for the 5G network, the exposure level can be reduced as the mmW architecture will use higher carrier frequency with smaller Inter-site distance (ISD) than the micro-wave structure. However, this paper analyzes the maximum possible exposure that a human user can experience if the antennas do not have the power control or adaptive beamforming capability and if only mmW architecture is present with no interference. In other words, this work analyzes the possibility of any threat possible from a 5G network at the worst possible scenario.

C. Contributions

Three contributions of this paper can be highlighted and distinguished from the prior art.

Firstly, this paper analyzes the human RF exposure in the downlink. Most of the prior works studied an uplink only, while hardly paying attention to the suppression of RF fields generated by access points (APs) in a 5G network.

Secondly, this paper finds that SAR should also be considered in the determination of human RF exposure in mmW downlinks. Our simulations are performed for a 5G system based on the three-dimensional (3-D) model proposed by 3GPP [17], one of the promising technical specifications for 5G. The results show that even considering a shallow penetration into a human body due to high frequencies, a downlink RF emission can cause significantly higher SAR in mmW for short AP-UE distances. This effectively highlights the elevation in possible harmful impacts on human health, which can ignite higher interest in further research on the design of future cellular communications systems considering the impacts on human RF exposure.

Thirdly, it explicitly compares the human RF exposure in downlinks of 5G [17] to those of the legacy standards—i.e., Release 9 [18] (which was the last release by 3GPP before 4G was deployed representing the 3.9G technology) and Release 12 [19] (which presents 4G LTE-Advanced technology as one of the latest Releases by 3GPP as the concurrent systems). This paper calculates PD and SAR of all aforementioned systems to provide a clear understanding of how the technical evolution to 5G can affect the human RF exposure.

III. SYSTEM MODEL

This section describes the system setting for the three cellular communications network that forms the basis for the analysis of human RF exposure in this paper. Though mmW frequencies start from 30 GHz according to literature, we consider the frequency spectrum of 28 GHz, which is very close to the starting point of mmW frequency, as a potential candidate for 5G. Since both Release 14 [17] and Release 15 (which provides more definitions for 5G) shares the same technical specification, this work, in other sense, represents also the performance of Release 15. The parameters of the three systems are summarized in Table I.

A. 5G and Release 12

1) Path Loss: Our model for 5G systems and Release 12 both consist of 19 sites each having 3 sectors. Since our analysis suggests Rural Macro (RMa) scenario does not possess any possible threat to human user for its higher ISD even in 5G, for the terrestrial propagation between an AP and a UE, we focus on two scenarios: Urban Macro (UMa) and Urban Micro (UMi). The inter-site distance (ISD) is 200 meters (m) for UMi and 500 m for UMa and each sector is assumed to have 10 active UEs.

2) Antenna Beam Pattern: For a 5G and Release 12 AP, the attenuation patterns of an antenna element on the elevation and azimuth plane are given by [17][19]

\[
A_a(\phi) = \min \left\{ 12 \left( \frac{\phi}{\phi_{3db}} \right)^2, A_m \right\} \quad [dB] \tag{1}
\]

\[
A_e(\theta) = \min \left\{ 12 \left( \frac{\theta - 90^\circ}{\theta_{3db}} \right)^2, A_m \right\} \quad [dB] \tag{2}
\]

where \(\phi\) and \(\theta\) are angles of a beam on the azimuth and elevation plane, respectively; \(\phi_{3db}\) denotes an angle at which a 3-dB loss occurs which is 65°. Then the antenna element pattern that is combined in the two planes is given by

\[
A(\theta, \phi) = \min \left\{ A_a(\phi) + A_e(\theta) , A_m \right\} \quad [dB] \tag{3}
\]

where \(A_m(=30\, dB)\) is a maximum attenuation (front-to-back ratio) [17], but it can be higher in practice. Finally, an antenna gain that is formulated as

\[
G(\phi, \theta) = G_{max} - A(\phi, \theta) \quad [dB] \tag{4}
\]

where \(G_{max}\) is a maximum antenna gain.

B. Release 9

1) Path Loss: A cellular network operating on Release 9 is designed to form a cell radius of 1500 m and 500 m, which results in an ISD of 3 kilometers (km) and 1 km for UMa and UMi, respectively. This paper calculates the received power in a downlink, following the path loss models provided in [18] for UMa and UMi.

2) Antenna Beam Pattern: The antenna radiation pattern for a Release 9 BS is also given as (1) and (2). However, unlike at a 5G AP, \(\theta_{3db}\) and \(A_m\) for a Release 9 BS are given as 35° and 23 dB, respectively.
TABLE I
PARAMETERS FOR 5G, RELEASE 12 AND RELEASE 9

| Parameter          | 5G                  | Release 12 (4G LTE-Advanced) | Release 9 (3.9G) |
|--------------------|---------------------|------------------------------|------------------|
| Carrier frequency  | 28 GHz              | 2 GHz                        | 1.9 GHz          |
| System layout      | UMa, UMi [17]       | Same as 5G                   | UMa, UMi [18]    |
| Inter-site distance (ISD) | 500 m (UMa) and 200 m (UMi) | 3 sectors/site               | 3 or 6 sectors/site |
| Cell sectorization | 3 sectors/site      | 3 sectors/site               |                  |
| Bandwidth          | 850 MHz             | 20 MHz                       | 20 MHz           |
| Max antenna gain   | 8 dBi per element   | 8 dBi per element            |                  |
| Transmit power     | 21 dBm per element  | 49 dBm (UMa) and 44 dBm (UMi) | 43 dBm          |
| AP’s number of antennas (λ/2 array) | 8×8                | 4 [20]                       |                  |
| AP antenna height  | 25 m (UMa) and 10 m (UMi) | 25 m (UMa) and 10 m (UMi)    | 32 m            |
| Duplexing          |                      | Time-division duplexing (TDD) |                  |
| Transmission scheme|                    | Single-user (SU)-MIMO        |                  |
| UE noise figure    | 7 dB                |                              |                  |
| Temperature        | 290 K               |                              |                  |

IV. PERFORMANCE ANALYSIS

In this section, we present our analysis on the human RF exposure in a 5G communications, a Release 12 and a Release 9 system. Though we chose 28 GHz frequency spectrum for 5G performance analysis, performance for any other frequency spectrum can be demonstrated following the same methodology. It is obvious that higher number of elements used in the antenna give better signal power, but it results in increased cost and complication of the antenna design. The Release 9 technology has a large cell size where a single BS can provide coverage to more than thousands of meters, but the cell size of 5G is relatively small. In a model like Release 9, there may be one BS used to provide coverage to a wide area, but in a 5G scenario, the same area is covered by a number of scattered APs to provide a better reliable service.

A. Data Rate

The downlink performance of a system is calculated from the Shannon’s formula, which is given by

\[ R = B \log_2 (1 + \text{SNR}) \]  

(5)

where \( R \) and \( B \) denotes a data rate and bandwidth, respectively. Signal-to-noise power ratio (SNR) is used to determine a data rate. Note that the inter-cell interference is not considered for simplicity in the calculation as the focus of this paper is to analysis of human exposure level, which is not influenced by the interference. In this paper, we calculate an SNR for the UEs considering all the possible locations in a sector that is formed by an AP in a 5G system and a BS in a Release 12 or Release 9 system. However, an accurate three-dimensional distance is considered with the exact heights of an AP, BS, and UE which are taken into account referred from [17]. In other words, although the horizontal axes of the results provided in Section V present all the possible locations in a cellular system, they, in fact, demonstrate 3-D distances with the exact vertical distances accounted.

The core part in the calculation of a bit rate is the received power that is directly determined by a path loss model provided in the specifications [17-19]. Here we provide an analytical framework for the signal power that is received by a UE from either an AP or a BS in a single downlink, denoted by \( P_{R,\text{ue}} \). It is noteworthy that with straightforward modifications, this framework can easily be extended to an uplink received signal power also. A received signal strength in a downlink transmission of a single sector is computed by averaging over all possible downlink directions according to the position of the UE, which is given by

\[ P_{R,\text{ue}}(x_{\text{ue}}) = \frac{1}{|R_k^2|} \int_{x_{\text{ue}} \in R_k^2} P_{T,\text{ap}} G_{\text{ap}}(x_{\text{ue}}) G_{\text{ue}}(x_{\text{ue}}) P_{L_{\text{ap}}\rightarrow\text{ue}} dx_{\text{ue}} \]  

(6)

where \( R_k^2 \) is region of a sector and thus \( |R_k^2| \) is the area of a sector; \( x_{\text{ue}} \) is position of a UE in an \( R_k^2 \); \( P_{T,\text{ap}} \) is transmit power of an AP; \( G_{\text{ap}} \) and \( G_{\text{ue}} \) are the antenna beamforming gains of an AP and a UE, respectively, in a downlink transmission based on \( 4 \); \( P_{L_{\text{ap}}\rightarrow\text{ss}} \) is the path loss between the AP and the UE.

B. Human RF Exposure

The expression for PD radiated by a transmit antenna at a far-field distance \( d \) is given by

\[ S_i = \frac{P_T G_T}{4\pi d^2} \]  

(7)

where \( P_T \) is a transmit power; \( G_T \) is a transmit antenna gain; \( d \) is the AP-UE distance (m) as in \( 6 \). The SI unit of PD is watts per m² (W/m²).

The SAR is a quantitative measure that represents the power dissipated per body mass. It is one of the International System of Units (SI), which is measured in watts per kilogram (W/kg).

We can write an SAR in terms of \( d \) for calculation in a cellular communications system, which is also a function of \( \phi \) [15], as

\[ \text{SAR}(d) = \text{SAR} (\phi) = \frac{2S_i (\phi) T (\phi) m (\phi)}{\delta \rho} \]  

(8)

where \( T \) is the power transmission coefficient [14], \( \rho \) is the tissue mass density (kg/m³), and \( \delta \) is the skin penetration depth (m) at 28 GHz [12]. The function \( m(\phi) \) [14] is dependent on the tissue properties of dielectric constant (\( \epsilon^* \)). The SAR
values differ according to the kind of tissue taken into consideration. For instance, SAR value for tissues in the limbs are different than the SAR value for any tissue within the eyes. Also, SAR at the surface of the exposed tissue is different from the SAR deep within that exposed tissue. However, unlike evaluations of SAR or temperature, evaluations based on PD do not rely on knowledge of the distribution of fields or power absorption in the tissues but only on the density of power traveling towards the tissue \([\ddagger]\). Hence, PD is not likely to be as useful as SAR for assessing safety in mmW fields.

In order to accurately study a mmW signal propagation and absorption in a human body, investigation on the parameters related to dielectric measurements on human skin are necessary. Specifically the values of the parameters, \(\rho, \varepsilon^*, \delta, T,\) and \(m(\phi)\) are obtained from prior related work \([11][12][17][21]\).

\[\text{V. EVALUATION OF HUMAN RF EXPOSURE}\]

In this section, we analyze our findings and compare the results between the three cellular systems (specified above) to have a clear view of the maximum threats possible from a 5G network with mmW architecture.

\[\text{A. Data Rate}\]

We consider an antenna array size of \(8 \times 8\) for 5G analysis. The BS antenna size for Release 12 \([20]\) and Release 9 both consist of 4 antenna elements as specified in Table I.

Fig. 1 shows the data rates that can be achieved in a 5G, a 4G LTE-Advanced (Release 12) and a 3.9G (Release 9) systems to represent the downlink performances. It can be seen that a UE in both 5G scenarios can yield a maximum downlink data rate above 13 Gbps. However, this performance may decrease in a practical case when interference is considered.

It should be emphasized from Fig. 1 that in spite of the disadvantage in propagation due to the higher carrier frequency, a 5G system presents approximately 15-times higher downlink rates compared to a Release 12 and approximately 20-times higher downlink rates compared to a Release 9 system. The main rationale behind such a significant outperformance is the beamforming antenna structure with high gains and smaller ISD in a 5G system. It is thus evident that the 5G mmW technology provides significantly better performance to the consumer as it provides better signal strength with higher data transmission capabilities at the user end.

\[\text{B. Human RF Exposure}\]

Now we show that even considering such shallow penetration depth due to high frequencies, a downlink RF emission can cause significantly higher SAR in mmW while the PD can still remain lower than the concurrent systems. As mentioned that it still remains not concluded in the literature which of PD and SAR is more appropriate to represent the human RF exposure level in far-field RF propagations, this paper claims that SAR should not be excluded in the measurement of human RF exposure in mmW downlinks. The rationale is that in spite of shallower penetration into a human body compared to lower frequencies, a mmW RF field causes a higher SAR due to (i) smaller cell radius and (ii) higher concentration of RF energy per beam via adoption of a larger phased array.

Figs. 2 through 5 take detailed looks at the human exposure to RF fields in downlinks. Each result specifies a path loss scenario (UMa or UMi) and the measurement metric (PD or SAR). Note that every result is an average taken over 10,000 drops of UE distribution in each sector or cell. As described in \([6]\) of Section IV-A the UEs are uniformly distributed on a two-dimensional space \(\mathbb{R}^2\) representing a sector.

Figs. 2 and 3 compare the PD between the downlinks of 5G, 4G LTE-Advanced and 3.9G. It can be seen that the PDs for 4G LTE-Advanced and 3.9G are higher than 5G in a UMa scenario. Small cell, one key enable technology of 5G, leads to lower transmission power. This feature of 5G systems leads to a smaller net effective isotropic radiated power (EIRP) for a 5G \([17]\) than a 4G LTE-Advanced \([19]\) or a 3.9G systems \([18]\) in a UMa scenario. However, the PD value for 5G technology falls below the safety level of 10 W/m\(^2\) \([6]\) after an AP-UE distance of just 60 m.
Figs. 4 and 5 compare the SAR in the downlinks of the three systems. While the SAR requirements for near-field is stated in [1], there is no standard provided for SAR in far-field so far based on a belief that SAR does not have a significant effect on human body in far-field.

Our results in Figs. 4 and 5 present that a 5G downlink yields a higher level of SAR at a human user. The main reason can be identified as the shorter propagation distance—namely, near-field—due to adoption of (i) small-cell topology and (ii) beamforming antennas with larger phased arrays. This is supported by the observation that in 4G LTE-Advanced (with smaller phased arrays) and 3.9G (with a larger ISD) yield a longer propagation that is sufficient fall down to a low enough SAR. The mmW beamforming antenna radiations with higher gains, larger phased arrays and smart antenna characteristics of 5G architecture keeps the SAR value in 5G higher in more areas in a network than a 3.9G or 4G LTE-Advanced.

Another striking observation is found with application of the ICNIRP guideline that is inferred from the case of lower frequencies—i.e., 10 MHz-10 GHz. As shown in Fig. 4 in a UMa path loss model, a 5G UE must be away at least by 125 m for experiencing a microwave exposure that is lower than the guideline. Applying the same logic leads to a finding in Fig. 5 that a 5G UE in a UMi model receives a downlink microwave at higher levels than the guideline in every possible position in a cell.

This high exposure in a 5G downlink can motivate further discussions. According to the ICNIRP guidelines [7], the maximum allowable SAR level for head and trunk is 2 W/kg and for limbs it is 4 W/kg for 10 g of tissue over 6 minutes of exposure for frequencies up to 10 GHz for general public (ICNIRP and FCC [6] do not have SAR guidelines for mmW like 28 GHz far-field scenario yet, as it is expected to be less dangerous). But our results presented in Figs. 4 and 5 show a significant increase in SAR in 5G downlinks compared to the 3.9G or the concurrent technology, even in such far-field propagations. Considering the significance of a regulatory guideline in the societal endeavor to prevent injuries from over-exposure, this paper hereby strongly urges that it is not safe enough with the PD solely being considered as a basic restriction in human RF exposure in mmW operations. Our result suggests that the SAR should also be considered as a measuring parameter even for far-field, particularly in mmW communications due to its received signal strength remaining strong at an end user.

VI. CONCLUSIONS

This paper has highlighted the significance of human RF exposure issue in the downlink of a cellular communications system. This paper measured the exposure level in terms of PD and SAR and compared them to those calculated in the Release 9 and Release 12 specifications. Distinguished from the prior art that studied uplinks only, this paper has found that the downlinks of a 5G can also yield significantly higher level of emissions compared to a concurrent network.
at the worst possible case. Our results emphasized that the increase stems from more highly concentrated RF energy per downlink RF beam due to use of larger phased arrays within small cells of a 5G network. However, only skin effects are being taken into consideration for simplicity and the network for 5G is considered to be under solely mmW infrastructure. If both mmW and microwave networks work combined and the antennas are equipped with the adaptive power transmission and beamforming capability depending on the AP-UE distance, the possibility of any user to be exposed to any possible threat in the downlink can be reduced.

But, to this point, unlike the prior work, this paper claims that RF fields generated in downlinks of 5G can also be dangerous in spite of far-field propagations. Therefore, we here urge the design of cellular communications and networking schemes that force an AP to avoid generation of RF fields if pointed at a human user with an angle yielding a dangerous level of PD and SAR. To this end, this paper identifies as the future work proposition of techniques that reduce human exposure to RF fields in 5G downlinks.

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