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A Simple Propagation Model to Characterize the Effects of Multiple Human Bodies Blocking Indoor Short-Range Links at 28 GHz

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Abstract: This study aims to provide a simple approach to characterize the effects of scattering by human bodies in the vicinity of a short-range indoor link at 28 GHz while the link is fully blocked by another body. In the study, a street canyon propagation characterized by a four-ray model is incorporated to consider the human bodies. For this model, the received signal is assumed to be composed of a direct component that is exposed to shadowing due to a human body blocking the link and a multipath component due to reflections from human bodies around the link. In order to predict the attenuation due to shadowing, the double knife-edge diffraction (DKED) model is employed. Moreover, to predict the attenuation due to multipath, the reflected fields from the human bodies around the link are used. The measurements are compared with the simulations in order to evaluate the prediction accuracy of the model. The acceptable results achieved in this study suggest that this simple model might work correctly for short-range indoor links at millimeter-wave (mmWave) frequencies.

Keywords: 5G; double knife-edge diffraction; human blockage; millimeter-wave; street canyon

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1. Introduction

It is widely known that the fifth-generation (5G) wireless systems will use millimeter-wave (mmWave) frequencies. However, the shorter wavelengths of mmWave signals render the efficiency of such systems susceptible to obstacles that lay in the environment. Thus, the performance of 5G communication systems needs to be properly assessed by evaluating the environmental conditions. For this reason, characterizing the propagation in indoor environments has recently become of great interest to researchers. In this context, several campaigns have been conducted to characterize the propagation channel at millimeter-wave bands [1].

When indoor scenarios are considered, propagation in mmWave frequencies suffers greatly from human blockage because of low-height directional or omni-directional antennas and low transmission power. Furthermore, the dielectric properties of human skin are another important factor that can be taken into account in order to study mmWave propagation characteristics, especially when radiating sources are close to the human body [2]. Then, in a broad sense, the received signal is the sum of several contributions (i.e., multipath signals), yet it is significantly affected by the propagation loss due to human blockage. Hence, it is necessary to provide an accurate human blockage model for human interactions like reflection and shadowing. In this context, various models have been proposed in the literature to investigate the characteristics of human-body blockage on indoor

propagation links [3–14]. Mostly, these models physically define a blocking object to estimate the realistic blockage loss by using mathematical formulas based on the diffraction of plane waves. One of the most popular models is the perfectly conducting circular cylinder model that is used in human effect investigations [3–5], but it is relatively computationally difficult and can be complicated in some cases. Alternatively, absorbing-screen models such as the double knife-edge diffraction (DKED) [7–9] and multiple knife-edge diffraction (MKED) models [10–14] are used to define a blocking object. In the DKED model, the diffracted fields from the two vertical sides of an absorbing screen are utilized. In the MKED model, diffraction from each side of the screen is considered. When compared to the DKED model, the MKED model provides better prediction accuracy and reflects a variety of real situations. However, the DKED model remains popular for modelling the human body due to its simplicity. Moreover, it is also important to note that artificial intelligence (AI) models have recently attracted a great deal of attention for detecting the human body shadowing effect [15].

On the other hand, it is already known that an indoor link is highly affected by multiple human blockages around it [16,17]. For this reason, the effects of multiple human blockages in the vicinity of the link at mmWave frequencies have also started to attract researchers in recent years. In order to investigate the attenuation caused by multiple human blockages, the blockers have been modelled as absorbing screens of multiple knife edges [8,11,18,19]. As these efforts are relatively limited, we believe that there are still open questions about the link attenuation at mmWave frequencies caused by multiple human bodies in indoor propagation scenarios. Hence, it is necessary to conduct more measurements in a variety of indoor propagation scenarios at mmWave frequencies in order to properly characterize the effects of multiple human bodies.

1.1. Related Works and an Overview of the Proposed Approach

In order to characterize the effects of multiple human bodies, one of the proposed methods is based on a physical optics approach to calculate the diffraction around the blockers [8]. In the work, the blockers are modeled as infinite absorbing screens with two knife-edges. The measurements were conducted in a conference room. The distance between the transmitter (T_x) and the receiver (R_x) was 7 m, and the height of the horn antennas was 1 m. In the measurements, two- and three-person scenarios were chosen. The blockers were moved perpendicular to the link. The distance between each blocker was 1 m along the horizontal axis. To evaluate the prediction error of the proposed method, the measurements were compared with the simulations.

Another work aims to extend the human-shadowing model proposed in [10] by multiple human bodies [11]. It uses the same methodology as in [10], where the approach is based on ray-tracing simulations carried out in conference room scenarios. As a difference, up to 10 persons were simulated in this more realistic scenario. The blockers were modeled as absorbing screens with multiple knife-edges. For the simulations, a random starting position was also assigned to each blocker to perform an individual random walk. In this way, the effects of multiple persons on the channel characteristics were investigated at 60 GHz. The accuracy of the model was evaluated by the statistics derived for both the root-mean-square (RMS) delay spread and the received power.

Furthermore, the work presented in [18] investigated the attenuations caused by multiple human bodies at 26 and 39.5 GHz. The human body was considered as an infinite absorbing screen with two knife-edges. To predict the attenuations, Vogler's multiple knife-edge model was used. The measurements were conducted at a restaurant where the distance between the T_x and the receiver R_x was 15 m and the height of both the T_x and the R_x was 1.3 m. In the measurement scenario, the blockers were moved perpendicular to the link (both frontal and lateral crossing). The distance between each blocker was 3.75 m along the horizontal axis. The measurements were then compared with the simulations to investigate the human-body attenuation and to validate the proposed model.

On the other hand, a simple approach based on a diffraction propagation model was recently presented in [19]. It characterized the effects of scattering by a human body near a short-range indoor link while another body was fully blocking the link. In fact, it was a unique study of the obstructed line-of-sight (OLOS) case to experimentally characterize the effects of scattering by multiple human bodies at 28 GHz. The measurements were conducted in a laboratory room. The height of both the T_x and the R_x was 1 m and the distance between them was 2 m. In the measurement scenario, the link was laterally blocked by a person. Meanwhile, another person laterally approached the link. Based on this scenario, a diffraction propagation model was incorporated to consider two human bodies. In this case, the total path loss was calculated, which was the product of two factors: (a) the loss in the direct path, which is the product of the free space path loss and the shadowing loss of the human body blocking the link; and (b) the shadowing loss of the human body approaching the link. Here, the shadowing loss of each blockage was calculated by using the DKED model for the sake of simplicity. The accuracy of the proposed model was then evaluated by comparing the simulations with the measurements. Although the proposed model worked well for simple indoor links, the prediction accuracy of the model tended to be reduced when the moving blocker was away from the link. Therefore, it would be better to examine the efficiency of the model in cases where more than two human bodies are considered.

The work presented in this paper investigates the effects of multiple human bodies for an OLOS case as considered in [19]. The difference is that the movement of two blockers is considered. In fact, for this scenario, the DKED-based approach [19] could be directly adapted. However, as mentioned above, one of the important concerns is this approach's prediction accuracy when the moving human bodies are away from the link. Therefore, in this work, a simple approach based on both diffraction and reflection mechanisms is expected to achieve better prediction accuracy. The main contributions of this work are provided in the following subsection.

In Table 1, the relevant works on the characterization of the effects of multiple human bodies blocking indoor propagation links at mmWave frequencies are listed and compared with the proposed approach.

Table 1. Comparison between the related works and the proposed approach.

Ref.	Approach	Measurement	No. of People (Max.)	Scenario	Frequency
[8]	Piazzi physical optics method	Yes	3	Crossing perpendicular to the link (in parallel)	60 GHz
[11]	Ray tracing	No	10	Random walk	60 GHz
[18]	Vogler's multiple knife-edge model	Yes	3	Crossing perpendicular to the link (in parallel)	26 & 39.5 GHz
[19]	DKED-based diffraction model	Yes	2	Approaching the fully obstructed link	28 GHz
Proposed Approach	Both DKED- and street-canyon-based models	Yes	3	Approaching the fully obstructed link	28 GHz

1.2. Contributions

This study can be considered as an extension of the work presented in [19]. The main purpose of this study is to provide a simple approach for characterizing the effects of scattering by two human bodies in the vicinity of a short-range indoor link at 28 GHz while the link is fully blocked by another body. In order to consider three human bodies, a simple propagation model is incorporated. In the model, the received signal is assumed to be composed of a direct component that is exposed to shadowing as well as a multipath component due to the reflections from the human bodies. To predict the attenuation due to shadowing, the DKED model is employed. On the other hand, to predict the attenuation due to multipath, the reflected fields from the moving human bodies near the link are used. This approach is based on the street-canyon propagation characterized by the four-ray model. To the best of the authors' knowledge, this simple model represents the first characterization of the effects of multiple human bodies around short-range indoor links at mmWave frequencies. The accuracy of the model is evaluated by comparing the measured received powers with the simulations. In addition, the accuracy of the DKED-based model presented in [19] is tested for the propagation scenario under consideration and compared with the proposed model. In summary, the main contributions of this study include the following:

- This is the first experimental study that provides a simple model to characterize the effects of scattering by two human bodies around the short-range indoor link at 28 GHz while the link is blocked by another body.
- For simplicity, both the street-canyon propagation characterized by a four-ray model and the DKED model are employed to elaborate the effects of multiple human bodies for the first time in the literature.

The remainder of the paper is organized as follows. We begin by describing the measurement system in Section 2, followed by the measurement campaign in Section 3. The proposed model is described in Section 4, and comparison results of the model simulations to a set of measurements are discussed in Section 5. The last section concludes the paper.

2. Measurement System

The measurement system used in this study is similar to the one in [19]. Briefly, as shown in Figure 1, the system is comprised of a spectrum analyzer (Agilent E4448A), a signal generator (Agilent E8244A), a T_x, and an R_x. At the T_x and the R_x, two identical horn antennas (PE9850/2F-20) with 20 dBi of gain and 16.7° vertical and 18.3° horizontal half-power beamwidth (HPBW) were used. In the system, the R_x was connected to the spectrum analyzer while the T_x was connected to the signal generator. All connections were made by means of low-loss cables (FE3C0747LF-200CM). Moreover, the antennas were mounted on a stand with 1 m height, where the distance between the stands was 2 m.

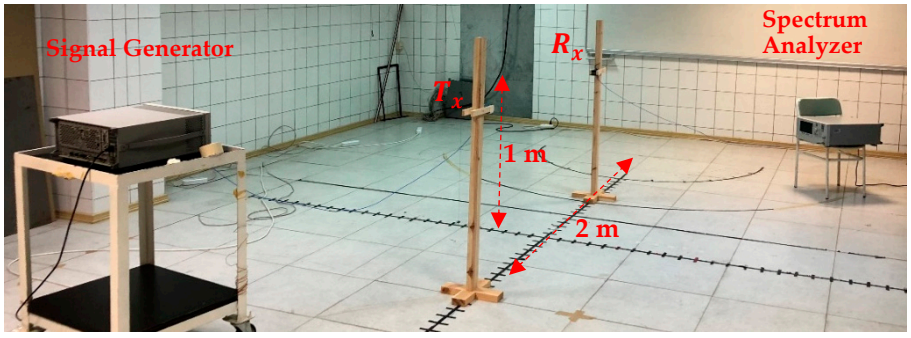


Figure 1. Measurement system.

Some preliminary studies were carried out before the measurements to ensure ideal measurement conditions. First, the measurement system was calibrated. Then, the effects of multipath signals caused by fixed objects in the measurement environment were investigated. Accordingly, it has been concluded that multipath signals can be neglected when considering their positions in the measurement environment [19].

While performing the measurements, the received powers were measured with the human blockers moving step by step. Measurements were repeated three times to ensure the stability of the system. The mean value of these measurements was then calculated and recorded.

3. Measurement Campaign

In order to investigate the loss caused by the human bodies and to validate the proposed model, a measurement campaign was conducted involving three participants in a laboratory room. In the scenario, the propagation link was laterally blocked by a person. At the same time, the other two persons simultaneously approached the link laterally, as shown in Figure 2. The body widths of the persons approaching the link were 0.5 and 0.48 m, respectively, and the body width of the person blocking the link was 0.49 m. While performing the measurements, one of the individuals approaching the link was moved from –1 m to –0.6 m, whereas the other one was moved from 1 m to 0.6 m. Here, the movements were limited to –0.6 m and 0.6 m to avoid overlap. After every 10 cm step, the received power was measured from 5 positions.

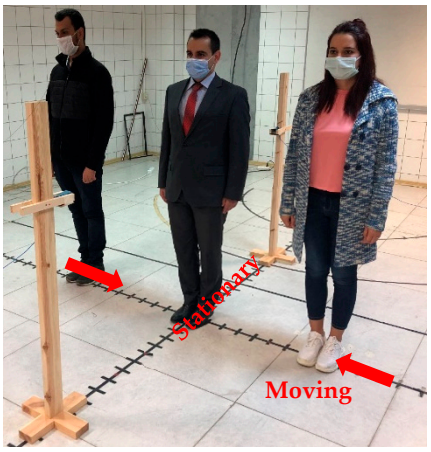


Figure 2. Measurement scenario.

4. Modelling of Scattering by Human Bodies

In this section, the proposed propagation model for the measurement scenario is presented. However, in order to provide a better understanding, a brief explanation of the four-ray street-canyon model and the DKED model is provided before presenting the proposed model.

4.1. The Street Canyon Model

Basically, the reflections on the building faces or the walls on both sides of the street are utilized in a street-canyon propagation [20]. The propagation is hence characterized by deterministic ray-tracing models. Among these, the two-ray model is the simplest model that uses both a direct or line-of-sight (LOS) ray (R_0) and an indirect ray reflected from the ground (R_0'), as shown in Figure 3. The electric field at the R_x (E_0) is then obtained as

$$E_0 = \sqrt{(G_{T0}G_{R0})}\frac{\lambda}{4\pi}\left(\frac{exp(-j2\pi r_0/\lambda)}{r_0} + \Gamma\frac{exp(-j2\pi r_0'/\lambda)}{r_0'}\right) \quad (1)$$

where r_0 and r'_0 are the distances of the direct and indirect paths, respectively, λ is the carrier wavelength, Γ is the ground reflection coefficient, and G_{T0} and G_{R0} are the gains of the T_x and the R_x, respectively.

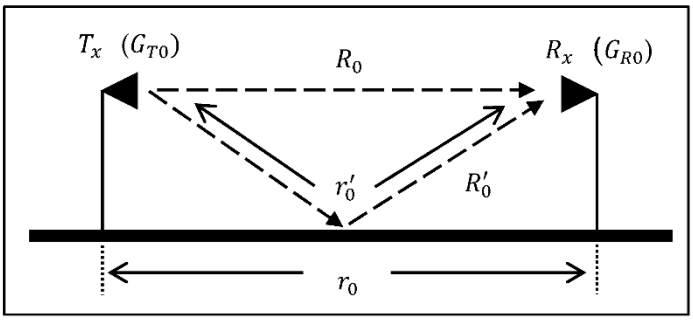


Figure 3. The two-ray model.

For the street-canyon propagation, it is necessary to extend the two-ray model in order to consider the rays reflected from the walls on both sides of the street. This can be achieved by adding more rays [21]. In this context, for simplicity, street-canyon propagation can be characterized by the four-ray model by adding two rays. The model then consists of R_0, R'_0, and Wall 1 and Wall 2 reflections (R_1, R_2) as depicted in Figure 4. Thus, based on (1), the total electric field at the R_x is obtained as

$$E_{four-ray} = E_0 + \sum_{i=1}^{2} \sqrt{(G_{Ti}G_{Ri})}\frac{\lambda}{4\pi}\left(\frac{exp(-j2\pi r_i/\lambda)}{r_i}\right) \quad (2)$$

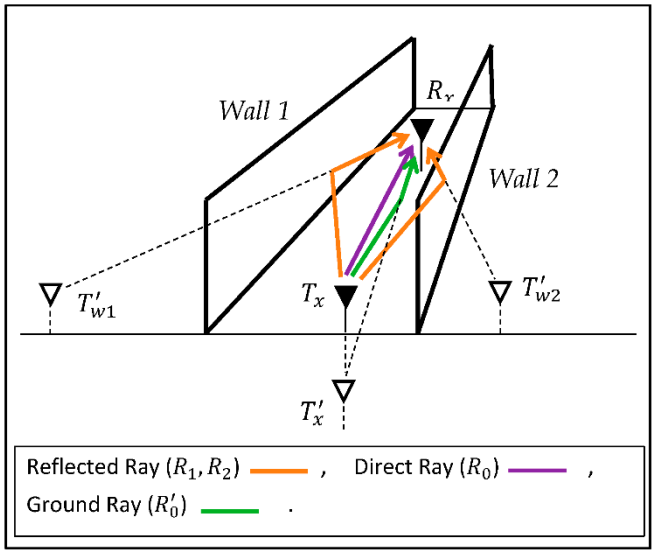


Figure 4. The four-ray model.

4.2. The DKED Model

In the DKED model, the loss caused by the human body can be estimated where a blocker is represented as a screen with two even vertical sides, as shown in Figure 5a [7–9]. Here, the height of the screen is assumed to be infinitely vertical for simplicity.

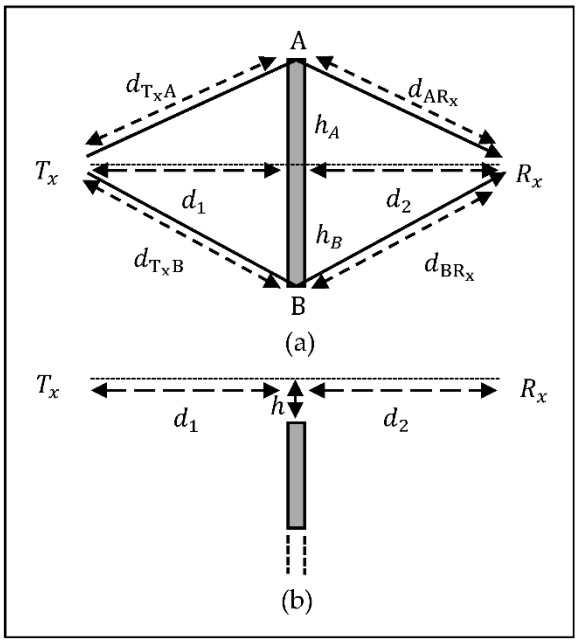


Figure 5. (**a**) The double knife-edge diffraction (DKED) model (top-view); (**b**) Half-plane absorbing screen.

Fundamentally, when a half-plane absorbing screen that obstructs the link as shown in Figure 5b is considered, the electric field at the R_x can be expressed as

$$E = \frac{1+\mathrm{j}}{2}\left\{\left(\frac{1}{2} - C(v)\right) - \mathrm{j}\left(\frac{1}{2} - S(v)\right)\right\}E' \tag{3}$$

where E' denotes the electric field at the R_x in the LOS case, and $C(v)$ and $S(v)$ are the Fresnel integrals:

$$C(v) + \mathrm{j}S(v) = \int_0^v e^{\frac{j\pi t^2}{2}}\mathrm{d}t \tag{4}$$

where v is the Fresnel–Kirchoff parameter [22]:

$$v = -h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1} + \frac{1}{d_2}\right)} \tag{5}$$

The total field at the R_x is then calculated by considering the DKED problem as given in Figure 5a. In this case, the diffracted field from each side of the screen that is observed at R_x (E_A, E_B) is solved using (3), where the E' can be calculated from

$$E' = \frac{\lambda}{4\pi(d_1 + d_2)}e^{(-\mathrm{j}2\pi f\frac{d_1+d_2}{c})} \tag{6}$$

where c is the speed of light. Thus, the total field can be given as follows [4]

$$E_{\mathrm{DKED}} = E_A e^{(-\mathrm{j}2\pi f\frac{\Delta d_{\mathrm{A}}}{c})} + E_B e^{(-\mathrm{j}2\pi f\frac{\Delta d_{\mathrm{B}}}{c})} \tag{7}$$

where $\Delta d_{(\mathrm{A,B})} = d_{\mathrm{T_x(A,B)}} + d_{\mathrm{(A,B)R_x}} - d_1 - d_2$.

4.3. The Proposed Model

A top-view of the measurement scenario is illustrated in Figure 6a. It is evident that propagation from the T_x to the R_x can be observed as the diffraction occurring on each side of the human blocker in the link together with the reflections taking place over the link side of the moving human blockers. Based on the illustration of the measurement scenario,

the propagation model can be depicted as shown in Figure 6b. Here, the human blocker on the link is represented as a rectangular screen with two sides in the top-down view. Furthermore, by utilizing Figure 4, the link side of the moving human blockers is assumed to be represented as a virtual wall in order to consider the reflection mechanism. Then, simply, the total field at the R_x (E_{total}) is the product of the fields due to the reflections from the blockers approaching the link, and the diffraction of the blocker on the link. Therefore, to estimate the E_{total}, we revise the expression given in (2) by replacing the E_0 with the improved version of the E_{DKED} given in (7). In the improved version of the E_{DKED} (E'_{DKED}), the diffraction fields are weighted by considering the antenna patterns. Thus, the E_{total} can be expressed as follows

$$E_{total} = E'_{\mathrm{DKED}} + \sum_{i=1}^{2} \sqrt{(G_{Ti}G_{Ri})}\frac{\lambda}{4\pi}\left(\frac{exp(-j2\pi r_i/\lambda)}{r_i}\right) \tag{8}$$

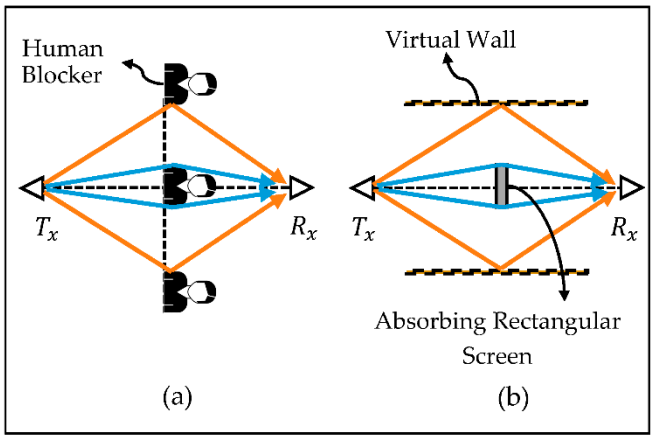


Figure 6. (**a**) Illustration of the measurement scenario; (**b**) Propagation model (top view).

5. Measurement Results and Discussion

This section is devoted to discussing the validity and applicability of the proposed model. First, the DKED-based diffraction model simulation [19] is compared with the received power from the measurements in order to examine its prediction accuracy when the moving blockers are away from the link. Next, the proposed model simulation is compared with both the received power from the measurements and the DKED-based diffraction model simulation. In this way, the accuracy of the proposed model is validated, especially for the case where the moving blockers are away from the link. Then, the applicability of the proposed model is discussed.

Before discussing the results, it should be noted that the simulation results are highly dependent on both the T_x and the R_x antenna gains, as discussed in [19]. In order to achieve consistent results, the radiation pattern of the antenna used in the measurements was validated by conducting some preliminary measurements. To do this, a half circle with a 1 m radius was drawn in front of the T_x, and measurements were taken by replacing the R_x at every 10° through the half circle as depicted in Figure 7a. Then, as shown in Figure 7b, the results were compared with the radiation pattern ordinarily given in the antenna datasheet. Consequently, the measured antenna gains were validated within a 2–10 dBi margin of error and used in the model simulations.

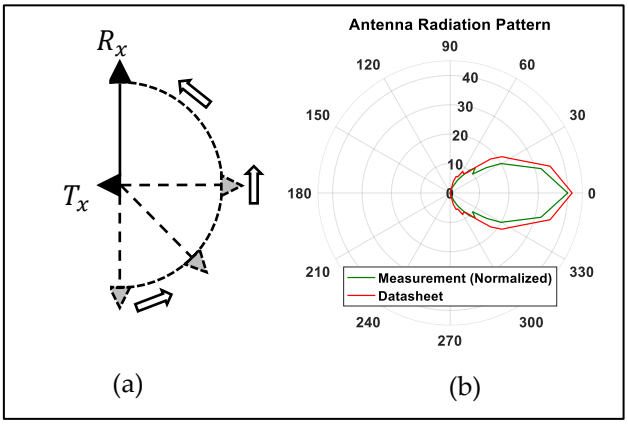


Figure 7. (**a**) Illustration of the measurement of antenna gains; (**b**) Comparison of the radiation patterns.

It should be also noted that the measured data and the simulation data obtained by using both the DKED-based diffraction model and the proposed model were normalized before the comparisons. To do this, three independent datasets were created, one of which consisted of the received power from the measurements while the other two consisted of the received power predicted by the DKED-based model simulation and the proposed model simulation, respectively. Here, the predicted received power from the proposed model was obtained by calculating the powers of E_{total} provided in (8). The normalized received power for each dataset was then computed by subtracting the maximum value of the dataset from each value. Thus, the datasets containing the normalized powers were compared. The comparison results are shown in Figure 8.

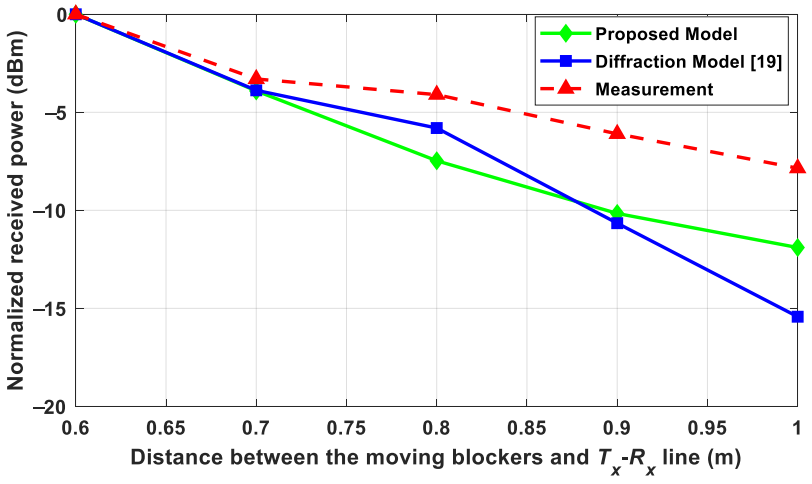


Figure 8. Comparison of the normalized received powers from the measurements and the simulations.

First of all, it is clear that the prediction accuracy of the DKED-based diffraction model is acceptable at some positions where the moving human blockers are close to the link. However, when the blockers are further away from the link (between 0.8 m and 1 m), the accuracy of the model tends to decrease. This result coincides with the result obtained in [19]. Here, the MKED model could be used as an alternative to the DKED model to achieve better accuracy. However, in this case, the computational complexity would be increased, which in turn would reduce the simplification benefits of the diffraction modelling at the expense of accuracy.

On the other hand, when compared with the DKED-based diffraction model, the proposed model exhibits better prediction accuracy in cases where the moving blockers are

further away from the link. Specifically, when they are positioned at 1 m, an approximately 4 dBm improvement in the prediction accuracy can be clearly observed. Overall, although the proposed model underestimates the measured received powers by 4 dBm at some positions where the moving blockers are further away from the propagation link, we believe that such accuracy is still acceptable.

According to the results, it can be concluded that the proposed model could be an efficient approach for characterizing the effects of human bodies for the considered measurement scenario. Nevertheless, some concerns about its applicability for many realistic situations should be addressed. One of the concerns is related to T_x and R_x antennas that are not at the same height. In practice, it is expected that the link would be mostly obstructed by the belly or chest area of the human body. For this reason, in the measurements, the heights of the T_x and R_x antennas were planned to be the same in order to provide proper alignment. Still, the proposed model is theoretically applicable for different antenna heights, as it utilizes basic geometric computations of the scattering mechanisms. Another concern could be linked with the distance from the three human bodies in the measurements, which might be greater in a realistic scenario. In this case, the effects of the moving human bodies would be decreased, and the propagation from the T_x to the R_x could be observed as only the diffraction occurring on each side of the human blocker on the link. Hence, the proposed model would approximate the DKED model. Therefore, this case was ignored in the measurements. Otherwise, it would not be possible to elaborate the effects of nearby human bodies around the short-range indoor links. Moreover, it is highly possible that the gain of the antennas might have considerable impact on the prediction accuracy of the proposed model. In this context, antenna gains at each position of the blockers should be correctly measured in order to ensure consistent and accurate results. Furthermore, in this study, a single result is shown in Figure 8 to compare the proposed model with the measurement results instead of providing additional analysis. This is because the main purpose of this study was to validate a simple but accurate propagation model to characterize the effect of two human bodies around the short-range indoor link at 28 GHz when the link is fully blocked by another human body. However, in the near future, we aim to conduct more analyses to show that the proposed model can be also used to evaluate the impact of human crowd activity on indoor link performance at mmWave bands.

6. Conclusions

In this work, the effect of scattering by human bodies around a short-range indoor link at 28 GHz while the link is fully blocked by another body is studied by theoretical modeling and measurements. The accuracy of the model is evaluated and validated by comparing the measured received powers with the model simulations. Based on the comparisons, we conclude that the proposed model provides acceptable results and better prediction accuracy when the moving blockers are farther away from the link. Therefore, it is believed that this study could be useful for many researchers working on the modelling of multiple human bodies near the indoor short-range links of 5G systems. The encouraging results obtained in this study might also aid in analyzing the effect of human crowd activity on the short-range indoor link performance at mmWave frequencies.

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