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DOI

[10.1109/LWC.2021.3093197](https://doi.org/10.1109/LWC.2021.3093197)

Publication date

2021

Document Version

Accepted author manuscript

Published in

IEEE Wireless Communications Letters

Citation (APA)

Kizhakkekundil, S., Morais, J., Braam, S., & Litjens, R. (2021). Four Knife-Edge Diffraction with Antenna Gain Model for Generic Blockage Modelling. *IEEE Wireless Communications Letters*, 10(10), 2106-2109. <https://doi.org/10.1109/LWC.2021.3093197>

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Four Knife-Edge Diffraction with Antenna Gain Model for Generic Blockage Modelling

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Abstract—With the recent adoption of millimeter-wave spectrum in cellular communications, deployment of active antenna arrays and use of beamforming become vital to compensate for the increased path loss. However, directional high-frequency signals may suffer heavy attenuations due to blockage effects. Therefore, blockage modelling that adequately incorporates the effects of beamforming becomes increasingly relevant. We propose a Four Knife-Edge Diffraction with antenna Gain (4KED-G) model, a deterministic approach to model blockage with broad applicability. The 4KED-G model advances upon the existing models in its inclusion of both angular antenna gains and the diffraction from all the four edges of a rectangular screen blocker, leading to a more general and flexible blockage modelling approach compared to existing widely accepted blockage models. We theoretically show that the proposed generalised model incorporates the strengths of these existing models, while overcoming their shortcomings in establishing applicability to wider range of blockage scenarios. We validate the generalised model against known knife-edge diffraction blockage models for specific scenarios.

Index Terms—blockage modelling, Knife-Edge Diffraction

I. INTRODUCTION

In current wireless networks, the tendency is to employ antenna arrays with an increasing number of antenna elements to leverage the benefits of beamforming, i.e. to increase received signal strength and decrease interference [1]. That is especially possible and needed at mmWave frequencies where the reduced wavelength permits packing more antenna elements in the same form factor [2]. Because high-frequency directional transmissions are particularly susceptible to quality degradation due to blockers [3], current radio network planning/optimisation tools must accurately predict the impact of a blocker [1]. To this end, the blockage event must be modelled.

Mainly three techniques exist to model a blocking event in a deterministic manner [3]. Geometrical Theory of Diffraction (GTD) [4] and its upgraded version the Uniform Theory of Diffraction (UTD) [5] require principles of electromagnetic field theory, making them computationally complex [3]. Knife-Edge Diffraction (KED) [6] is less computational demanding [3], while still fitting measurements satisfactorily. That is why KED is often used to model blockage effects [3], [7]–[10].

The limits of applicability of KED models have been studied thoroughly [11]. Most KED models only apply when the blocker is sufficiently distanced from both transmission ends [11], because such models do not take into account the radiation pattern of antennas [7]–[9]. Therefore, they are restricted to scenarios where the antenna gains are practically constant across the blocking object [10]. To increase the range of possible positions and sizes of blockers, one must consider antenna gains [10].

Nonetheless, KED-based models without antenna gains have been widely used because they are simple and, under certain conditions, effective. METIS [7] proposed a Double Knife-Edge Diffraction (DKED or 2KED) which approximates blocking objects by giving them an infinite height. Understandably, such assumptions work properly for a specific range of blockers, in particular, those for which the height is roughly three times larger than the width [10]. Also, the approximation of a blocker with an infinite number of sides/edges by just two diffracting edges is done with a specific blocker in mind, a standing human [9]. For blockers with different shapes/size ratios, it is proven that considering diffractions on multiple edges (MKED), normally four-edges (4KED), fits measurements better than DKED [3], [9].

To the best of our knowledge, the newly proposed general blockage model incorporating both the four-edge finiteness of blocking objects and the effects of a realistic antenna radiation pattern, does not yet exist in literature. Current models either consider four edges or consider antenna gains [3], and examples are the 4KED model [8], and the 2KED-G model [10], [12], respectively. Despite being largely theoretical in nature, the key contribution of the proposed blockage model lies in its expanded domain of applicability, with validation checks performed to demonstrate the match with existing 2KED, 2KED-G and 4KED models and their validating measurements [3], [9], [10].

The letter is organised as follows. Section II describes the proposed 4KED-G model. Section III compares the proposed model with 4KED and 2KED-G with simulations. Section IV summarizes and concludes this letter.

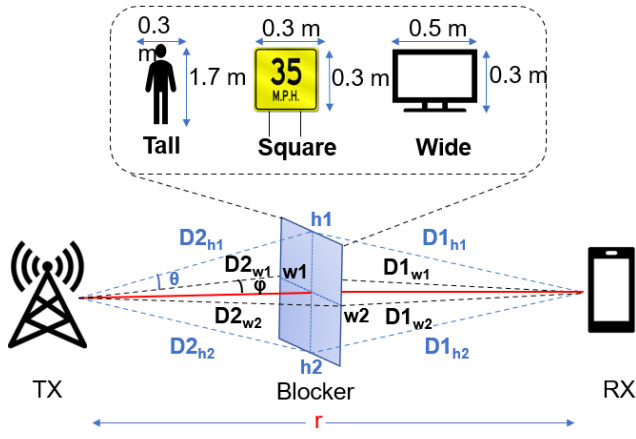


Fig. 1: Illustration of projected distances and angles from the TX and RX to the blocker for LOS blockage modelling.

II. PROPOSED MODEL

In this section we derive a model which incorporates the essence of the 4KED [8] and the 2KED-G [10] models such that blockers with a generic size can be modelled for scenarios involving directional transmissions.

KED models consider a perfectly conducting blocker screen [2]. Since the penetration loss is far greater than the diffraction loss for relatively opaque blockers, it is possible to consider only the power diffracted on the edges [2].

Figure 1 illustrates the geometric relation between the blocker, the transmitter (TX) and receiver (RX). The infinitesimally thin blocker of height h and width w blocks the line-of-sight (LOS) between RX and TX. Depending on the ratio between w and h , we classify the blocker as tall (e.g. human), square (e.g. speed sign), or wide (e.g. widescreen monitor). The TX and RX are distanced r meters. $D1_i$ and $D2_i$, with $i \in \{h1, h2, w1, w2\}$, denote the distances from TX and RX to all sides of the blocker (projected on horizontal and vertical planes). θ and ϕ denote the elevation and azimuth angles between LOS and $D1/2_i$ in the vertical and horizontal planes, respectively. Equations (2), (3) and (4) give the attenuation loss in dB, respectively, for 4KED [8], 2KED-G [10] and 4KED-G.

In the loss equations, F_i is a measure of the shadowing (diffraction) at each of the four edges of a knife-edge blocker, and is given by Equation (1). F_i belongs to $(-\infty, \frac{1}{2}]$, reaching the highest value when the attenuation is maximal, so practically no power is diffracted on that edge, and the lowest when

$$F_{h1/h2/w1/w2} = \frac{1}{\pi} \tan^{-1} \left(\pm \frac{\pi}{2} \sqrt{\frac{\pi}{\lambda} (D1_{h1/h2/w1/h2} + D2_{h1/h2/w1/w2} - r)} \right) \quad (1)$$

$$L_{AKED} = -20 \log_{10} (1 - (F_{h1} + F_{h2}) (F_{w1} + F_{w2})) \quad (2)$$

$$L_{2KED-G} = -20 \log_{10} \left[\left(\frac{1}{2} - F_{w1} \right) \sqrt{G_{D2_{w1}}} \sqrt{G_{D1_{w1}}} + \left(\frac{1}{2} - F_{w2} \right) \sqrt{G_{D2_{w2}}} \sqrt{G_{D1_{w2}}} \right] \quad (3)$$

$$L_{4KED-G} = -20 \log_{10} \left[1 - \left[1 - \left[\left(\frac{1}{2} - F_{h1} \right) \sqrt{G_{D2_{h1}}} \sqrt{G_{D1_{h1}}} + \left(\frac{1}{2} - F_{h2} \right) \sqrt{G_{D2_{h2}}} \sqrt{G_{D1_{h2}}} \right] \times \left[1 - \left[\left(\frac{1}{2} - F_{w1} \right) \sqrt{G_{D2_{w1}}} \sqrt{G_{D1_{w1}}} + \left(\frac{1}{2} - F_{w2} \right) \sqrt{G_{D2_{w2}}} \sqrt{G_{D1_{w2}}} \right] \right] \right] \quad (4)$$

the attenuation is practically zero. In case a certain edge i does not intercept the LOS, the distance D_i should be accounted as negative.

G_{D1_i} and G_{D2_i} represent the linear gains of RX and TX antennas, respectively. The gains are computed based on projected angle (θ , ϕ), and normalised to the LOS gain, i.e. $G(\theta = \phi = 0^\circ) = 1$. We compute the gains of an array with the cross-polarized antenna elements defined by 3GPP in [13], which results in practically the same gain as the analytical expression in [10]. Lastly, λ denotes the carrier wavelength.

When omnidirectional antennas are considered, or when radiation patterns are ignored, normalised gains become unity and the 4KED-G equation in (4) turns into the 4KED equation in (2). When $F_i = \frac{1}{2}$ for $i \in \{h1, h2\}$, which corresponds to extending those edges to infinity, then equation (4) of 4KED-G turns into equation (3) of 2KED-G.

III. RESULTS AND ANALYSIS

In this section we demonstrate the attenuations predicted by the 4KED, 2KED-G, and 4KED-G models with simulations using the channel generator Quadriga [14] and the channel model 'LoSonly'. We evaluate link blockage for a sub-6 GHz frequency (3.5 GHz) and a mmWave frequency (26 GHz).

In the scenario considered for analysis, as illustrated in Figure 1, the LOS passes through the centre of the blocker and the attenuation due to the blocker is calculated for a range of blocker positions between the TX and RX. The TX-RX distance r is fixed to 5 meters and the antenna arrays are facing each other at a height of 1.5 meters. We consider three different blocker dimensions, chosen as representatives of different categories of blockers: tall, square and wide. To analyse the effect of directionality we consider three different Half Power Beam Widths (HPBWs), by changing the number of elements on the antenna arrays, as indicated in Table I. The TX and RX antennas are the same and the inter-element spacing is kept at half-wavelength.

The models are evaluated for different blocker positions along the LOS, for all combinations of the aforementioned three blocker sizes and three antenna arrays. The nine charts are present in Figure 2. Each row represents a specific blocker and each column a specific HPBW, with each frequency color-coded. The vertical axis shows the relative power, the ratio between the received power without the presence of a blocker and that with the presence of a blocker.

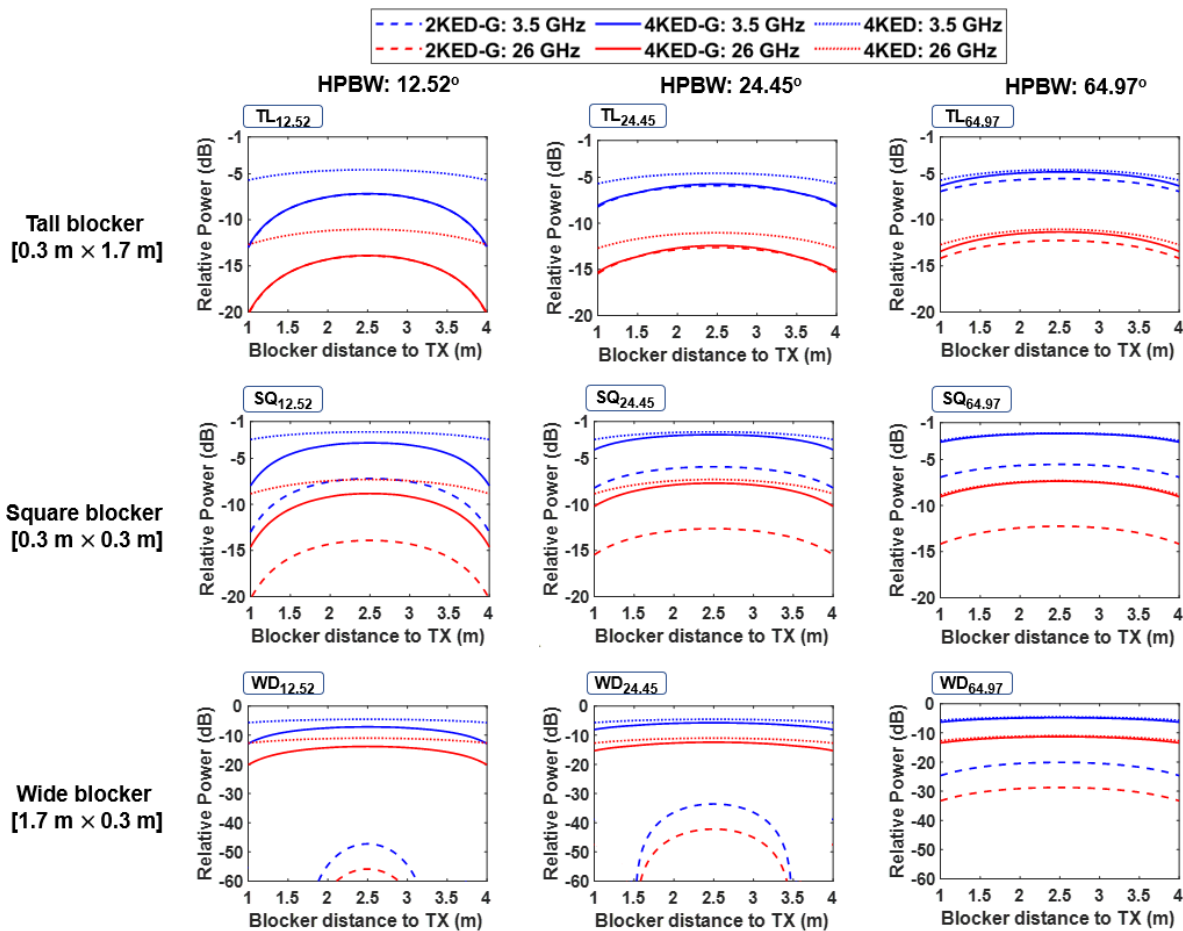


Fig. 2: Comparison of attenuation resulting from tall, square and wide blockers and three distinct antenna HPBW's (12.52°, 24.45°, 64.97°) for 2KED-G, 4KED-G and 4KED models.

TABLE I: TX/TX antennas and respective HPBW's.

Antenna array size (row × column)	Azimuth/Elevation HPBW
8 × 8	12.52°
4 × 4	24.45°
1 × 1	64.97°

Regardless of the model, we see that an increase in HPBW results in decreased attenuation caused by the blocker, owing to the fact that an increase in beamwidth leads to an increase in the normalised gain. Also, we observe that the attenuation is always lower in 3.5 GHz than in mmWave spectrum, because the shadowing loss is inversely proportional to the wavelength in Equation (1), which is in line with the higher susceptibility to blockages at higher frequencies [1]. The charts further show that the 4KED-G model predicted attenuation always lies between that of the 2KED-G and 4KED models. As the HPBW increases for a specific blocker, the attenuation curve of 4KED-G approaches the 4KED curve since an increase in beamwidth causes the gains on the edges to get closer to the maximum, i.e. $G_{D1/2i} \rightarrow 1$.

Concentrating on the top row of charts, we see that the

4KED-G model matches near-perfectly the attenuation results obtained and validated by the 2KED-G model [10] for scenarios with human (tall) blockers. The smaller the HPBW and hence the narrower the beams, the stronger the match. Another near-perfect match can be observed when comparing the attenuation levels of 4KED-G model with the 4KED model for the scenarios with wide transmissions, i.e. rightmost column of the charts, regardless of the considered blocker. Recalling that the 4KED model has been developed and validated for cases without highly directional transmissions [8], it makes sense that when the antenna gain across the blocker is almost constant (the case for high HPBW) we get more similar results. The demonstrated good match in these specific applicability scenarios was of course already mathematically clear from the modelling formulas, which degenerate to the 2KED-G and 4KED models for the corresponding conditions.

The key contribution of the proposed blockage model lies in its applicability to a much wider range of scenarios, which are not covered by previously existing models. For instance, the 2KED-G model is not intended for non-tall blockers. Thus for blockers whose size is rather limited in the vertical dimension, as is the case for the analysed examples of the

square and wide blockers, the 2KED-G model overestimates the attenuation (and hence underestimates the received signal power) because it intrinsically expands the blocker to an infinite size in the vertical dimension. Looking to the highest HPBW for square and wide blockers (SQ_{64,97} and WD_{64,97}), the attenuation predicted by the 4KED model near-perfectly matches the measurement result [8], [9] while the attenuation predicted by the 2KED-G model deviates about 5 and 20 dB from the measurement value, respectively.

Likewise, if we look at a scenario with directional transmissions where 2KED-G models fits measurements well [10], like TL_{64,97}, we see that the 4KED model has a discrepancy with reality of almost 10 dB when the blocker is closer to the either the TX or RX, because it is where the difference between gains on the edges and maximum gain is larger. The discrepancy is due to the fact that the power diffracted on an edge is proportional to the gain in the direction of that edge and, since blockage models omitting the antenna gain effect assume maximum gain on every edge, they overestimate the diffracted power, and thus underestimate the attenuation caused by the blocker. The cases in between these extremes need to be further verified with measurements [15], [16], but the theoretical considerations strongly indicate that the more general 4KED-G model should be well-suited for covering a much wider range of scenarios.

Typically, the maximum difference between the proposed and the existing models is observed when the blocker is closest to either the TX or RX. To evaluate this difference, we fix the blocker position to 1 m from the TX and show the corresponding attenuations in Figure 3.

The magnitude of these differences highlight the utility of the proposed 4KED-G model with respect to the existing models. For scenarios with relatively wide blockers, the 2KED-G model is off the mark by at least 15 dB. For scenarios with directional beams, the 4KED model is off by at least 5 dB, and it would be considerably worse if the blocker would be closer to the TX or RX, in case of larger blockers or when transmissions in more directional, i.e. in scenarios where the gains in the directions of the edges are lower.

IV. CONCLUSION

In this letter, we have proposed the 4KED-G model, a generalisation of the existing 4KED and the 2KED-G models. The proposed model offers a large degree of flexibility in modelling a variety of blocking objects and estimating their attenuation impact while including directionality of the TX and the RX antennas in beamforming scenarios.

A partial validation showed that the blockage effect predicted by the proposed model indeed nicely matches that predicted by the verified 4KED [8] and 2KED-G [10] models for specific scenarios covered by those models. Furthermore, the 4KED-G model predicts plausible attenuations where the other two models do not apply, in particular, when the antenna gains need to be taken into account or when the blocker has a different size ratio than a human being, for the 4KED and 2KED-G models, respectively. Therefore, evidence

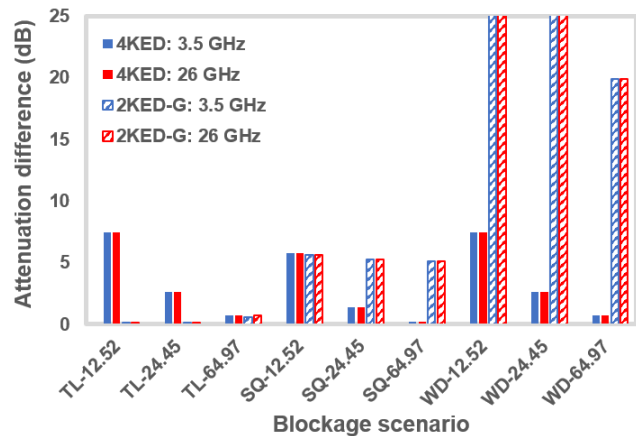


Fig. 3: Attenuation difference between 4KED-G and the other models for a blocker distanced 1 m from the TX.

suggests that our blocking model is a promising candidate to fit a broader class of blockers while supporting directional antennas. Nonetheless, further validation with measurements on a wider variety of scenarios is required to validate this.

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