On the Fraction of LoS Blockage Time in mmWave Systems with Mobile Users and Blockers

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Abstract. Today, one of the emerging trends for the next generation (5G) networks is utilizing higher frequencies in closer premises. As one of the enablers, small cells appear as a cost-effective way to reliably expand network coverage and provide significantly increased capacity for end users. The ultra-high bandwidth available at millimeter (mmWave, 30–300 GHz) and Terahertz (THz, 0.3–3 THz) frequencies can effectively realize short-range wireless access links in small cells. Those technologies could also be utilized for direct communications for users in proximity. At the same time, the performance of mobile wireless systems operating in those frequency bands depends on the availability of line-of-sight (LoS) between communicating entities. In this paper, we estimate the fraction of LoS time for randomly chosen node moving according to different mobility models in a field of N moving blocking nodes for both base station and device-to-device (D2D) connectivity scenarios. We also provide an extension to the case of a random number of moving blockers. The reported results can be further used to assess the amount of traffic offloaded to other technologies having greater coverage, e.g., LTE.

1 Background and Motivation

Due to tremendous increase in traffic demand, researchers in both industry and academia already focus on numerous advanced networking solutions such as client-relaying [1], heterogeneous networking [2], the use of micro/pico/femto cells [3] and Device-to-Device (D2D) communications [4–6] to satisfy the requirements of fifth generation (5G) mobile wireless systems. These mechanisms alone, however, are limited in achieving the required data rates.

One of the initial steps forward is moving up in the frequencies from microwaves to millimeter waves (mmWave, 30–300 GHz) [7] and further to the terahertz (THz, 0.3–3 THz) band [8] is considered as a viable solution to principally increase the capacity of wireless channels and eventually satisfy the requirements of 5G-grade networks. Operating at those frequencies could be described by the following

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features: (i) higher throughput; (ii) shorter propagation distances due to higher attenuation; (iii) better spatial resolution due to smaller beamwidth; (iv) smaller antenna size in general; and (v) higher blockage affection.

The principle discord between mmWave/THz systems, compared to microwaves, is that there is an extreme difference in the received signal strength in line-of-sight (LoS) and nLoS conditions [9,10]. Such systems are expected to be installed in open indoor and outdoor environments such as conference halls, lobbies, squares, crossroads, parks [11]. Nevertheless, as electromagnetic waves cannot "travel around" the objects whose size is smaller than their wavelengths while the human bodies serve as perfect absorbers [12], the crowd around the receiver blocks the LoS. To understand performance bounds of mmWave and THz systems, it is essential to predict the probability of having LoS at a particular instant of time as well as the fraction of time there is a LoS between communicating entities in crowded mobile environments.

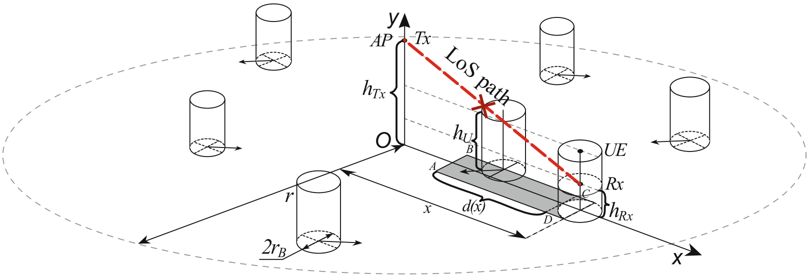
The question of the LoS propagation blockage has recently received particular attention from the research and standardization community [13,14]. As demonstrated by field measurements in [15], the loss of LoS path in mmWave systems may result in sharp drops of the (up to 30–40 dB) in the received signal strength. The first analytical studies on this topic addressed the question of LoS blockage in environments with static users and static blockers [16,17]. These results have been recently extended to the case of moving blockers and static users in [18] as well as static blockers and moving users in [19]. In these studies, it has been shown that the mobility of both blockers and users drastically affect the blockage statistics leading to additional uncertainly in channel state. However, to the best of the authors' knowledge, there have been no studies addressing the case when both blockers and users are simultaneously mobile.

In this paper, we derive the probability of having nLoS at a random instant of time as well as the fraction of LoS for a user in a group of $N + 1$ blockers moving around in closed indoor compartment according to the random direction mobility (RDM) and random waypoint (RWP) models. We consider mmWave access point (AP) and D2D scenarios and also sketch the extension to the open outdoor scenarios, where a user and blockers may freely enter and leave the service area of interest. The presented results can further be used to assess the amount of traffic that needs to be offloaded to another type of connection.

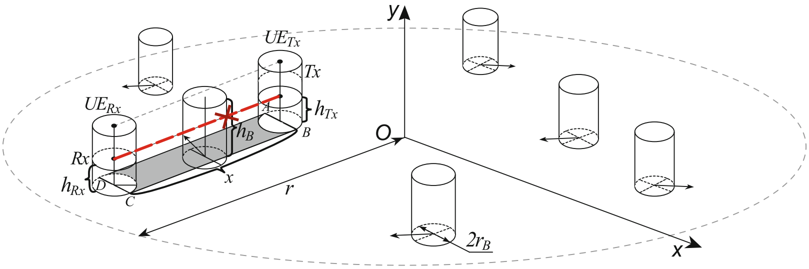
The rest of the manuscript is organized as follows. Section 2 provides the system model and depicts the scenarios of interest. Next, we elaborate on the applicability of the model to dynamic conditions and extend it in Sect. 3. The numerical examples are given in Sect. 4. The last section concludes the manuscript.

2 Indoor Closed Compartment Scenario

Two scenarios of interest are described in this section. We focus on both conventional infrastructure-based case, where AP serves the tagged user and the remaining ones act as potential blockers, and D2D scenario, where two users are attempting to initiate direct link that could be blocked by other users. Both users and blockers are mobile and move according to a RDM mobility model [20]. Recall that according to RDM a point first randomly chooses the direction of movement uniformly in $(0, 2\pi)$. Then, it moves in the chosen direction for exponentially distributed time with constant speed v. The process is restarted at the stopping point.



(a) LoS blocking zone for BS scenario.



(b) LoS blocking zone for D2D scenario.

Fig. 1. Considered scenarios.

2.1 Access Point Scenario

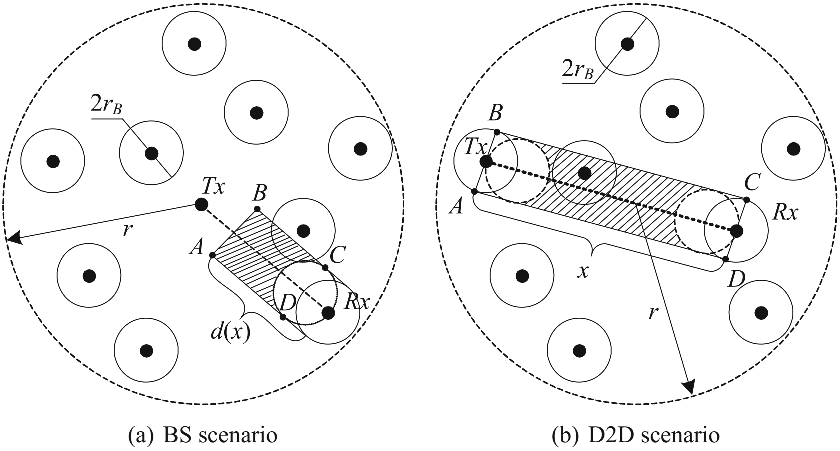
In the first scenario, we assume $N + 1$ mobile users (UEs), acting as blockers, that randomly move according to RDM in the coverage area with radius r of a mmWave or THz AP, which height is h_{Tx} (AP is selected as transmitter (Tx)). The height of the blockers is assumed to be the constant and equal to h_B. The radius of a blocker is r_B. The height of the receiver (Rx) associated with the tagged UE is $h_{Rx} < h_B$. We are interested in the probability of nLoS at the arbitrary time instant and the fraction of nLoS. Note that these metrics are symmetric irrespective of which entity (AP or UE) acts as Tx or Rx correspondingly.

We assume that UE is located at the distance x from the AP at time t, as shown in Fig. 1(a). The LoS to the UE could be blocked by the blockers that are located in the so-called *LoS blocking zone*, marked in gray. The length of this zone is

$$d(x) = \frac{x(h_B - h_{Rx})}{h_{Tx} - h_{Rx}}. \tag{1}$$

Observing the top view of the scenario, Fig. 2(a), notice that the area of the LoS blocking zone is more complicated than a rectangle. To prevent overlapping there cannot be a blocker located closer than at $2r_B$ to the user. The area of the LoS blocking zone is

$$S_B = 2r_B[x - d(x)] - 2r_B^2 - \frac{1}{2}\pi r_B^2. \tag{2}$$



(a) BS scenario (b) D2D scenario

Fig. 2. Top view of the LoS blocking zone.

The existence of the zone around the UE prohibiting the presence of blockers implies that the minimum distance from the AP resulting in non-zero LoS blocking zone is $2r_B$. Recall that the limiting distribution of the RDM is uniform over the area of interest [20]. Observing the system in stationary regime, the probability of a point uniformly distributed in the circle hitting an LoS blocking area is given by the ratio $S_B/\pi r^2$. Generalizing to N blockers, we arrive at

$$p_B(N) = 1 - \left(1 - \frac{2r_B[x - d(x)] - 2r_B^2 - \frac{1}{2}\pi r_B^2}{\pi r^2}\right)^N. \tag{3}$$

The probability density function (pdf) of a point uniformly distributed in a circle of radius r is given by $f(x) = 2x/r^2$. Thus, the probability of having nLoS at a random instant of time, p_{nL}, coinciding with the fraction of nLoS, f_{nL}, is

$$f_{nL} = \int_{2r_B}^{r} \frac{2x}{r^2} \left(1 - \left[1 - \frac{2r_B[x - d(x)] - 2r_B^2 - \frac{1}{2}\pi r_B^2}{\pi r^2}\right]^N\right) dx. \tag{4}$$

Integrating (4) we arrived at the final result in the following closed-form

$$f_{nL} = 1 - \frac{4r_B^2}{r^2} - \frac{\left[\frac{4(A-1)r_B^2+B+\pi r^2}{r^2}\right]^{N+1}\left[\pi r^2 - 4(A-1)(N+1)r_B^2 + B\right]}{2\pi^N(A-1)^2(N+1)(N+2)r_B^2} \tag{5}$$

$$+ \frac{\left[\frac{r(2(A-1)r_B+\pi r)+B}{r^2}\right]^{N+1}\left[r(\pi r - 2(A-1)(N+1)r_B) + B\right]}{2\pi^N(A-1)^2(N+1)(N+2)r_B^2}, \tag{6}$$

where the shortcuts are

$$A = \frac{(h_B - h_{Rx})}{h_{Tx} - h_{Rx}},\ B = 2r_B^2 - \frac{\pi r_B^2}{2}. \tag{7}$$

2.2 D2D Scenario

Since the height of Tx and Rx is assumed to be the same, $h_{Tx} = h_{Rx} < h_B$, it suffices to consider two dimensional case, as shown in Fig. 2(b). Given the distance x between Tx and Rx the area of the LoS blocking zone is

$$S_B(x) = 2r_B x - 4r_B^2 - \pi r_B^2. \tag{8}$$

Similarly to the AP blocking model, there is no blocking when Tx and Rx are closer than $4r_B$. Recalling the stationary property of RDM model and the fact that the distance between two points uniformly distributed in the circle of radius πr^2 is given by [21]

$$f(x) = \frac{2x}{r^2}\left(\frac{2}{\pi}\arccos\left(\frac{x}{2r}\right) - \frac{x}{r\pi}\sqrt{1 - \frac{x^2}{4r^2}}\right),\ 0 < x < 2r, \tag{9}$$

we have the following for the fraction of nLoS

$$f_{nL} = \int_{4r_B}^{r} f(x)\left(1 - \left(1 - \frac{2r_B x - 4r_B^2 - \pi r_B^2}{\pi r^2}\right)^N\right)dx, \tag{10}$$

that also coincides with the nLoS blocking probability. Note that the integral cannot be expressed in elementary functions but can be computed numerically.

3 Extensions and Applications

3.1 Outdoor Environment

The scenarios considered previously are unrealistic for outdoor deployments, where blockers/user may freely enter and leave an area of interest. For AP scenario this area coincides with the service area of aN AP while for the D2D case this is the area, where D2D connectivity is feasible, e.g., UE proximity characterized by the short-range radio coverage area. In this section, we address this by introducing dynamics to the model.

Let A_0 be the circular service area of an AP and let A_1 be the greater circular area where N blockers are allowed to move according to RDM. We are interested in the probability that a randomly chosen node currently located in the AP service area is in nLoS state. This probability no longer coincides with the fraction of nLoS as the latter needs to be obtained knowing the AP service area residence time of a user.

Recall that in the stationary regime N nodes moving in A_1 are uniformly distributed in A_1 [20]. Thus, the number of nodes in A_0 follow binomial distribution with parameter A_0/A_1 and these nodes are all uniformly distributed in A_0. Increasing A_1 and N such that $\lambda = N/S_{A_1}$ is kept constant $p = A_0/A_1 \rightarrow 0$ and the binomial distribution approaches the Poisson one with parameter λ. Thus, the probability of having LoS at the distance x, $p_L(x)$, is given by the void probability of a Poisson process with the area estimated in (2), i.e.,

$$p_L(x) = \exp\left(-\lambda\left[2r_B[x - d(x)] - 2r_B^2 - \frac{1}{2}\pi r_B^2\right]\right), \tag{11}$$

where $d(x)$ is provided in (1).

The probability that a node is moving according to RDM and located in A_0 at time t experiences nLoS conditions is obtained similarly to (4) with exponential blocking probability replacing the binomial one. It is provided in (12). For D2D scenario the integral for nLoS probability is similar to (10), with $1 - p_L(x)$ from (11) replacing the binomial blocking. It also cannot be solved in elementary functions but can be numerically evaluated with any given accuracy.

$$\begin{aligned} p_{nL} &= \int_{2r_B}^{r} \frac{2x}{r^2}\left(1 - e^{-\lambda\left[2r_B[x-d(x)]-2r_B^2-\pi/2r_B^2\right]}\right) = \\ &= 1 - \frac{e^{\lambda r_B([\pi+4]r_B-2r)}(2\lambda r r_B + 1) - 32\lambda^2 r_B^4}{2\lambda^2 r^2 r_B^2} + \frac{e^{(\pi-4)\lambda r_B^2}\left(8\lambda r_B^2 + 1\right)}{2\lambda^2 r^2 r_B^2}. \end{aligned} \tag{12}$$

To evaluate the fraction of nLoS for outdoor deployment, it is necessary to obtain the time corresponding to the UE staying in the service area A_0. This is a first passage time in a circle for a random point moving according to RDM with some initial position that depends on the size of A_0 and parameters of RDM model. Neither pdf nor mean of this metric can be obtained analytically [22]. Nevertheless, one could always use computer simulations or Brownian motion approximation of RDM (see [22], Chap. 4) to quantify this metric.

3.2 Further Extensions

We specifically note that the the model proposed in this paper can be extended in many different ways. First of all, one can use any mobility model having well-defined stationary distribution, for example, random waypoint (RWP) mobility model whose distribution in a square with side A is available in closed form [23], i.e.,

$$f_{X,Y}(x,y) = \frac{36}{A^6}\left(x^2 - \frac{A^2}{4}\right)\left(y^2 - \frac{A^2}{4}\right). \qquad (13)$$

The only additional step compared to the presented model is to determine the distance to the mmWave AP or the distance between two nodes. This can be done applying the random variables transformation technique. Notably, for the AP to UE case, the transformation of interest reads as $r(x,y) = \sqrt{x^2 + y^2}$ and the procedure is reduced to finding the Jacobian of the transformation [24].

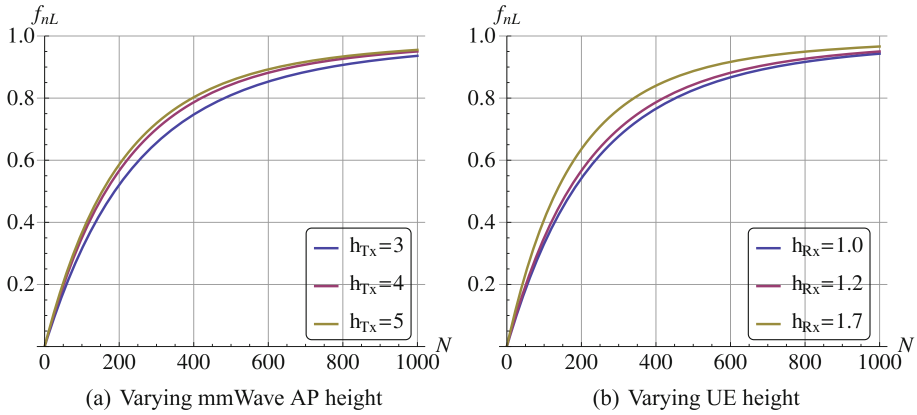
We also would like to specifically note that LoS blockage does not always lead to the outage event, i.e., for a given propagation model the outage even may only occur when the current distance between communicating nodes is higher than the specific value. The result for a fraction of time can be extended to this case as well. Considering AP to UE scenario as an example, we first obtain the fraction of time UE is farther than a certain propagation distance D, then observe that the UE position conditional on being farther than D is still uniformly distributed in the ring (D, R) with density $f(x) = 2x/(R^2 - D^2)$ and then determine the fraction of LoS blockage time using $f(x)$.

4 Numerical Illustrations

In this section, we illustrate the obtained numerical results. First, we consider the LoS blockage probability for AP to UE communications scenario. We then address D2D communications case. Finally, we consider the outdoor scenario with a Poisson distribution of the number of blockers.

Consider first the AP to UE indoor communications scenario. Figure 4 illustrates the fraction of LoS blockage time as a function of systems parameters including mmWave AP height, h_A, and UE height, h_U for a range of the number of blockers in the compartment. In these illustrations, the height of Rx is set to 1.2 m, and the height of blockers is 1.7 m. The radius of the coverage is 30 m. Expectedly, as the number of blockers increases the probability of LoS blockage increases. Further, it is essential to observe that the change in AP and UE heights does not drastically affect the blockage probability. The most significant effect stems from the number of blockers in the area.

The effect of input parameters on the fraction of LoS blockage time for the D2D scenario is illustrated in Fig. 4 as the function of the number of blockers for different radii of the service area. Recall that in this scenario the height of communicating entities is the same. Logically, by keeping the number of blockers constant and increasing the service area of interest the fraction of LoS blockage time increases. Finally, by comparing the results in Fig. 4 with Fig. 3(a) and (b), we observe that the fraction of the LoS blockage time for the D2D scenario is significantly bigger. The rationale is that in the case of D2D communications the heights of entities are all the same implying that the area of the LoS blockage zone is significantly larger.



(a) Varying mmWave AP height (b) Varying UE height

Fig. 3. Fraction of LoS blockage time in AP to UE scenario.

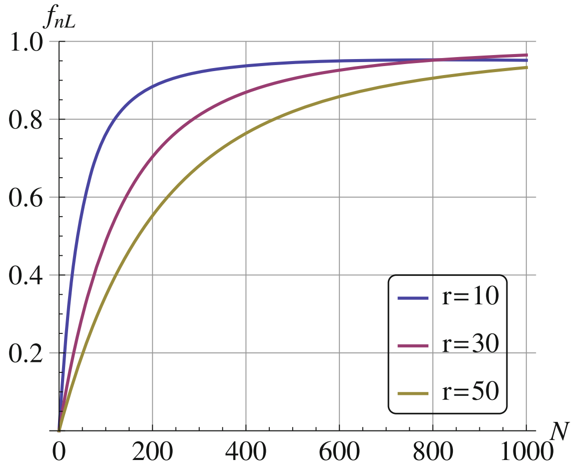


Fig. 4. The fraction of nLoS for D2D scenario.

Finally, we compare the fraction of LoS blockage time in indoor and outdoor scenarios for AP to UE case. The comparison is facilitated by parameterizing indoor model with the number of blockers corresponding to λS_A, where S_A is the service area of interest, where λ is the density of blockers in the Poisson model. The results are demonstrated in Fig. 5. As one may observe, the outdoor model with a Poisson distribution of a number of blockers is characterized by a much higher value of the fraction of the blockage time. The difference is maximized for medium values of the blockers density in the range (0.10–0.25) blockers per squared meter.

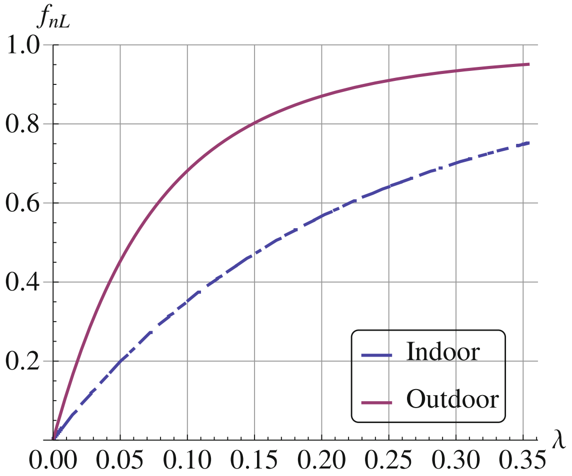


Fig. 5. Fraction of LoS blockage time in indoor and outdoor scenarios.

5 Conclusions

In this manuscript, we derived the probability of nLoS and the fraction of time a user spends in nLoS state in a group of N blockers moving according to RDM in the indoor closed compartment for both AP and D2D connectivity cases. We then provided the extension to the case for outdoor deployment, where UEs freely enter and leave the service area. Our results apply to performance analysis of mmWave and THz wireless systems.

The central application area of the proposed model is performance analysis of traffic offloading in heterogeneous multi-layer wireless access networks featuring mmWave and/or terahertz APs. Notably, the fraction of LoS blockage and/or outage time characterize the amount of time resources of systems have larger coverage, and usually smaller capacity needs to be used.

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