Blockage and Coverage Analysis with MmWave Cross Street BSs Near Urban Intersections

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***Abstract*—Millimeter wave (mmWave) communication offers Gbps data transmission, which can support massive data sharing in vehicle-to-infrastructure (V2I) networks. In this paper, we analyze the blockage effects among different vehicles and coverage probability of a typical receiver, considering cross street BSs near urban intersections in a multi-lane mmWave vehicular network. First, a three-dimensional model of blockage among vehicles on different lanes is considered. Second, we compute the coverage probability considering the interference of cross street base stations. Incorporating the blockage effects, we derive an exact and semi closed-form expression of the cumulative distribution density (CDF) of the association link path gain. Then, a tight approximation of the coverage probability is computed. We provide numerical results to verify the accuracy of the analytic results. We demonstrate the effects of blockage and the cross street interference. Also, we compare coverage probability with different BSs intensities under various street settings. It is shown that in multi-lane V2I networks, blockage among vehicles is not significant. Also, deploying more BSs does not increase coverage probability efficiently in ultra-dense streets.**

I. Introduction

Millimeter wave (mmWave) vehicle-to-infrastructure (V2I) communication is an effective way to exchange large data among vehicles [1][2]. To enhance driving safety, vehicles are equipped with a large number of sensors to collect and broadcast surrounding information, and make right decisions to avoid potential collisions. V2I is an alternative for exchanging raw data as it can serve as a sensor fusion hub, with connection to other BSs and sensors, while the availability of huge amounts of unused frequency bands at mmWave makes it possible for massive data sharing with roadside infrastructures [3][4].

Though there is a vast body of literature targeting at the analysis of mmWave cellular communication in urban scenarios [4–6], very limited work analyzes mmWave for V2I applications, in a much more complicated scenario, with substantial vehicle blockage and multi-path shadowing effects. Our analysis lies on the basis of the previous work of urban mmWave cellular analysis, for example, in [4], an analytic framework based on stochastic geometry was proposed to characterize the coverage probability considering building blockages in urban mmWave networks. In [7], a correlated shadowing model in urban networks was provided which considered the number of building blockages under a Manhattan Poisson line process (MPLP) street model. In [8], a new pathloss model based on Manhattan distance was proposed for urban microcells at mmWave band, which was adopted in our previous work [9]. Such a Manhattan distance based pathloss model also accommodates well with the stochastic geometry approach and generates tractable analysis [9].

In this paper, we provide a tractable framework to analyze blockage and coverage considering near intersection BSs on cross streets, in a multi-lane urban mmWave vehicular network. Different from previous work of urban mmWave cellular analysis, we consider a new scenario in vehicular networks, which incorporates Manhattan type streets and multiple lanes of vehicles into analysis. We also consider an important set of BSs, which are located on the cross streets near intersections blocked by buildings, while still offer direct links with LOS visibility. Finally, we formulate very tight approximations of the coverage probability of urban vehicular communication at mmWave.

II. System model

A. Network model: MPLP model

Fig. 1 illustrates the street and BS models in this paper. We consider a *typical* horizontal street in the middle of the urban area and cross (vertical) streets whose right sides are modeled as MPLP, with street intensity as λ_{s}. The regions outside the street are all assumed to be rectangular buildings, as shown in Fig. 1. We consider a *typical* receiving vehicle which is located on the typical horizontal street.

BSs are deployed only on the upper side and right side of the typical horizontal street as independent one-dimensional PPPs Φ_{th} and Φ_{tv}, with identical intensity as λ_{t}. Following the conclusion in [9] that NLOS BSs blocked by buildings have negligible effects on coverage and association, we only consider two types of BSs in this paper, respectively the BSs on the typical street as Φ_{H} and BSs in the LOS region (see Fig. 1) on cross streets Φ_{V}, which are free of building blockage. We make the following assumptions on the network model of BSs and streets.

Assumption 1. *We neglect the case when two parallel streets might overlap (due to street width), since the streets are generally sparse and the overlap is less likely.*

Assumption 2. *Under stochastic geometry, BSs dropped at the urban intersections are neglected, since such deployment has very small probability.*

Assumption 3. *BSs blocked by buildings on the cross and parallel streets are neglected, since they are not the major source of interference/BS association [9].*

B. Signal model

As is shown in [9], in urban microcells, propagation links that traverse the street corner and suffer from building blockages should be modeled by a Manhattan distance based pathloss model. In this paper, the links of interest are simply those free of building blockage, which are LOS visible. Hence, the pathloss can simply be modeled by standard power attenuation law, i.e., $\ell(r) = Ar^{-\alpha}$, where $r > 0$ is the length of the direct Euclidean distance and $A \in \mathbb{R}^+$ is a constant [7, 10, 11]. As the true nature of the pathloss is as of yet unknown, we are using a simple approximation here for analytic tractability. For this we associate different pathloss exponents for the blocked and unblocked cases, similar to [4], where the pathloss for unblocked and blocked links are modeled as $\ell_{\mathrm{L}}(r) = Ar^{-\alpha_{\mathrm{L}}}$ and $\ell_{\mathrm{N}}(r) = Ar^{-\alpha_{\mathrm{N}}}$.

We assume unit transmit power $P_{\mathrm{B}} = 1$ and denote the normalized noise power by N_0. To hold the tractability of analysis under stochastic geometry, all links are assumed to experience independent Rayleigh fading with mean 1, i.e., $h \sim \exp(1)$.

C. Modeling vehicles

There are two types of vehicles in the network: *large* (*blocking*) vehicles (e.g. trucks, ambulance, buses, etc.) and *small* vehicles (cars). We make the following assumptions.

1) The vehicles are assumed to be regular-shaped cubes.
2) The vehicle's trajectory follows the *center* of a lane.
3) The transceiver of a vehicle is located on the top and center of the vehicle.

Then, we assume each vehicle has fixed heights as H_{L} and H_{S}, width as $W_{\mathrm{V}}^{\mathrm{L}}$ and $W_{\mathrm{V}}^{\mathrm{S}}$, and length L_{L} and L_{S}, for large and small vehicles respectively. The typical receiver is a small vehicle, suffering from potential blockages of large vehicles. The lane width is denoted as W_{L}, and the total lane number is N_{L}. Hence, the street width is $W_{\mathrm{s}} = N_{\mathrm{L}} W_{\mathrm{L}}$. Large vehicles (blockers) on each lane are modeled as one-dimensional independent homogeneous PPP, with intensity as λ_{B}. We use Ω_m to represent the distance between the center of the mth lane to the road side where the BSs are deployed, which is defined as

$$\Omega_m = \left(m - \frac{1}{2}\right) W_{\mathrm{L}}. \tag{1}$$

We denote the *blocking distance* of a *blocking cone* generated by a large vehicle on mth lane as B_{C}^m, which will be explained in detail in Section III.

III. Blockage analysis

Thinking of the BS as a light source, we analyze the blockage pattern between the vehicles on different lanes. A three-dimensional *blocking cone* is generated and associated to each individual large vehicle. If the typical receiving vehicle lies inside the *blocking cone*, then it is blocked [12]. To facilitate analysis, we abstract out the *cross section* of the blocking cone in Fig. 2. In the following sections, we examine the effects of the three-dimensional blockage pattern and the blockage probability using stochastic geometry.

A. Characterizing blocking cone

Vehicles on different lanes are subject to different blockage effects. For example, vehicles on the lane closest to the roadside BS are free of blockage; large vehicles on the lanes further away from the roadside will generate larger blocking cones and the receivers on these lanes will be subject to more blockage as well. We then analyze the blockage patterns of two types of BSs, respectively on the typical street and the cross street with LOS visibility.

1) BSs from the typical street: From Fig. 2, we evaluate the blocking distance B_{C}^m of the blocking cone associated to a certain large vehicle on the mth lane. Based on the *similarity of triangles* (see Fig. 2), we derive the following equation

$$\frac{B_{\mathrm{C}}^m - \Omega_m - \frac{W_{\mathrm{V}}^{\mathrm{L}}}{2}}{B_{\mathrm{C}}^m} = \frac{H_{\mathrm{BS}} - H_{\mathrm{L}}}{H_{\mathrm{BS}} - H_{\mathrm{S}}}, \tag{2}$$

where the parameters are defined in Section II-C. Then,

$$B_{\mathrm{C}}^m = \frac{\Omega_m + \frac{W_{\mathrm{V}}^{\mathrm{L}}}{2}}{\left(\frac{H_{\mathrm{BS}} - H_{\mathrm{L}}}{H_{\mathrm{BS}} - H_{\mathrm{S}}}\right)}. \tag{3}$$

2) BSs on cross streets with LOS visibility: For the BSs on the cross streets, the blockage is more complicated since the signal crosses streets and potentially vehicles with different orientations. To simplify the model and retain the tractability of analysis, we treat the BS as an equivalent *virtual* BS located on the typical horizontal street, but the number of lanes between the roadside and the receiver is the same as that of lanes the propagation link actually crosses.

B. Blockage probability

Next, we focus on how many large vehicles might *potentially* block a receiver on mth lane. A receiver is potentially blocked by a vehicle V_k on kth lane, if the receiver's rooftop antenna lies inside the blocking cone associated with V_k. This is equivalent to the event that the center of the vehicle, Ω_m is located inside the blocking distance of the cone, i.e., $\Omega_m < B_{\mathrm{C}}^k$, $k \in \{1, \cdots, m-1\}$. We define the set of lanes on which a large vehicle could potentially block the vehicle on mth lane as $\mathcal{B}_m$, and

$$\mathcal{B}_m = \bigcup_{k \in \{1, \cdots, m-1\}} \left\{k : \Omega_m < B_{\mathrm{C}}^k\right\}, \tag{4}$$

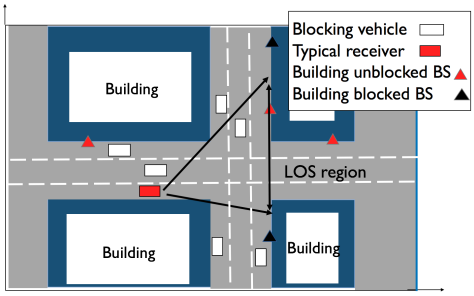

Fig. 1: Illustration of the street modeling with width and BS deployment.

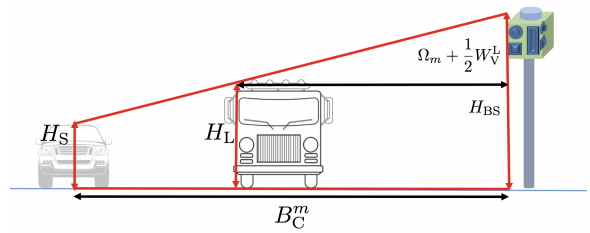

Fig. 2: Illustration of blockage distance and blocking cones among large and small vehicles on different lanes.

where Ω_m and B_{C}^{k} are respectively given in (1) and (3). Hence, the total number N_{B}^{m} of lanes whose vehicles might block the vehicle on mth lane is

$$N_{\mathrm{B}}^{m} = \text{cardinality}\{\mathcal{B}_m\}. \tag{5}$$

Assuming there are $N_{\mathrm{L}} = 4$ lanes on one street in total, giving different height of the BSs, the blockage number is shown in Table I[1] .

TABLE I: Number of Blockages

Lane Index	2	3	4	5*	6*	7*	8*
$h_{\mathrm{BS}} = 6$m	1	1	2	3	3	4	4
$h_{\mathrm{BS}} = 10$m	0	1	1	1	2	2	2
$h_{\mathrm{BS}} = 20$m	0	0	0	1	1	1	1

The table implies two intuitive results: i) the higher the BS, the fewer blockage the vehicle can have because the size of the blocking cone becomes smaller; ii) the further the receiver is, the blockage is more severe. Given the blockage number in (5), we use the following Lemma to derive the LOS probability for a typical street BS.

Lemma 1. *The probability that the typical receiver on the mth lane is not blocked is*

$$p_{\mathrm{L}}^{(m)} = \exp\left(-\lambda_{\mathrm{B}} L_{\mathrm{L}} N_{\mathrm{B}}^{m}\right). \tag{6}$$

Proof. The link being LOS is equivalent to that there is large vehicle within a L_{L} wide area on the kth lane ($k \in \mathcal{B}_m$). Since the distribution of large vehicles on different lanes is independent, the LOS probability is the product of the void probability of the PPP on each lane.

$$p_{\mathrm{L}}^{(m)} = \prod_{k \in \mathcal{B}_m} \exp(-\lambda_{\mathrm{B}} L_{\mathrm{L}}) = \exp\left(-\lambda_{\mathrm{B}} L_{\mathrm{L}} N_{\mathrm{B}}^{m}\right), \tag{7}$$

which concludes the proof. □

Note that we neglect correlation effects of the blockage, which are shown to be negligible [4].

IV. Coverage analysis

A. Pathloss modeling

For BSs on the typical street, due to the blockage effects of the vehicle, the interferers are thinned by the LOS probability (unblocked by vehicles) $p_{\mathrm{L}}^{(m)}$, generating two independent PPP of LOS and NLOS BSs, respectively with intensity as $\lambda_{\mathrm{t}}^{\mathrm{L}}(m) = \lambda_{\mathrm{t}} p_{\mathrm{L}}^{(m)}$ and $\lambda_{\mathrm{t}}^{\mathrm{N}}(m) = \lambda_{\mathrm{t}}(1 - p_{\mathrm{L}}^{(m)})$. We define the path gain of the link from the typical receiver on mth lane to the BSs on the typical street as $\ell^{(m)}(r) = \mathbb{I}(p_{\mathrm{L}}^{(m)})\ell_{\mathrm{L}}(r) + (1 - \mathbb{I}(p_{\mathrm{L}}^{(m)})))\ell_{\mathrm{N}}(r)$, where $\mathbb{I}(x)$ is the Bernoulli random variable with paremter x, $\ell_{\mathrm{L}}(r)$ and $\ell_{\mathrm{N}}(r)$ are the standard power attenuation law of LOS and NLOS links defined in Section II-B [4].

For BSs on the cross street, as is explained in Section III-A2, we approximate the blockage effect of the BS on cross streets with LOS-visibility by a horizontal BS located on a *virtual roadside* on a typical street which is Q lanes away from the receiver, where Q is the number of the lanes the propagation link actually crosses. With the virtual roadside BS modeling assumption,

$$Q = N_{\mathrm{L}} + m. \tag{8}$$

Define the distance from one cross street to the typical receiver as x, the upper and lower boundaries $L_1(x)$ and $L_2(x)$ of the LOS region on the cross street can be obtained by similarity of triangles, which are

$$L_1(x) = \frac{\Omega_m x}{x - W_{\mathrm{s}}} \quad \text{and} \quad L_2(x) = \frac{(W_{\mathrm{s}} - \Omega_m)x}{x - W_{\mathrm{s}}}, \tag{9}$$

Hence, for the BSs in the LOS region $-L_2(x) < y < L_1(x)$ on the cross street at x, path gain is

$$\mathrm{PG} = \ell^{(Q)}\left(\sqrt{x^2 + y^2}\right). \tag{10}$$

B. BS association

The LOS regions of typical receivers on different lanes all differ which yields a fairly tedious expression of the coverage. For more concise analysis, we assume that the LOS region is identical for a typical receiver on any lane, which generates symmetric LOS region and enables more tractable result.

Assumption 4. *The LOS length for the typical receiver on different lane is symmetric about the line that the receiver is on, i.e.,*

$$L(x) = L_1(x) = L_2(x) = \frac{x W_{\mathrm{s}}}{2(x - W_{\mathrm{s}})}. \tag{11}$$

[1]The $*$ in the table refers to the virtual lane explained in Section III-A2).

Assuming the receiver is associated to the BS with smallest path loss, then, conditioning on the associated link channel gain as v, the cumulative distribution density (CDF) of the associated link channel gain for the receiver on mth lane is provided in the following lemma.

Lemma 2. *We can approximate the CDF of the associated link channel gain as*

$$F(m,v) = \exp\left(-\mathcal{F}_{\mathrm{L}}(v,x)\right)\exp\left(-\mathcal{F}_{\mathrm{N}}(v,x)\right) \times \exp\left(-\lambda_{\mathrm{s}}\int_{W_{\mathrm{s}}}^{v^{-\frac{1}{\alpha_{\mathrm{L}}}}} 1-\mathcal{G}_{\mathrm{L}}(v,x)dx\right) \times \exp\left(-\lambda_{\mathrm{s}}\int_{W_{\mathrm{s}}}^{v^{-\frac{1}{\alpha_{\mathrm{N}}}}} 1-\mathcal{G}_{\mathrm{N}}(v,x)dx\right), \quad (12)$$

where

$$\mathcal{F}_{\mathcal{S}}(v,x) = 2\lambda_{\mathrm{t}}^{\mathcal{S}}(m)\sqrt{\min\{v,\Omega_m^{-\alpha_{\mathcal{S}}}\}^{-\frac{2}{\alpha_{\mathcal{S}}}}-\Omega_m^2}, \quad (13)$$

and

$$\mathcal{G}_{\mathcal{S}}(v,x) = \exp\left(-2\lambda_{\mathrm{t}}^{\mathcal{S}}(Q)\min\left\{\sqrt{\min\{v,x^{-\alpha_{\mathcal{S}}}\}^{-\frac{2}{\alpha_{\mathcal{S}}}}-x^2}, L(x)\right\}\right), \quad (14)$$

where $\mathcal{S}=\{\mathrm{L},\mathrm{N}\}$.

Proof. Proof is provided at [13]. □

C. Coverage probability calculation

We start with formulating the expression of the signal-to-interference-plus-noise ratio (SINR). The interference is comprised of the interference from BSs on the typical street $I_{\Phi_{\mathrm{H}}}$, BSs on cross streets $I_{\Phi_{\mathrm{V}}}$. Adopting the analytic framework from [9], conditioning on the associated link path gain as v, the SINR is

$$\mathrm{SINR} = \frac{hv}{I_{\Phi_{\mathrm{H}}}+I_{\Phi_{\mathrm{V}}}+N_0}, \quad (15)$$

and the coverage probability is defined as

$$\mathbb{P}\left(\mathrm{SINR}>T\right) = \mathbb{P}\left(h>\frac{T}{v}\left(I_{\Phi_{\mathrm{H}}}+I_{\Phi_{\mathrm{V}}}+N_0\right)\right) \overset{(a)}{=} \exp\left(\frac{TN_0}{v}\right)\mathcal{L}_{I_{\Phi_{\mathrm{H}}}}\left(\frac{T}{v}\right)\mathcal{L}_{I_{\Phi_{\mathrm{L}}}}\left(\frac{T}{v}\right), \quad (16)$$

where $\mathcal{L}_{(\cdot)}(s)$ is the Laplace transform (LT) of $(\cdot)$ with variable s, and (a) is based on the assumption of independent Rayleigh fading of each link and the fact that interference is independent for BSs on typical streets and cross streets. The approximate coverage probability is derived in the following Theorem.

Lemma 3. *Conditioning on the associated link path gain as v, the coverage probability of the vehicle on the mth lane can be approximated by*

$$p_{\mathrm{c}}(v,m,T) = \exp\left(-D_1 v^{-1}\right)\exp\left(-D_2^{\mathrm{L}} v^{-\frac{1}{\alpha_{\mathrm{L}}}} - D_2^{\mathrm{N}} v^{-\frac{1}{\gamma_{\mathrm{N}}}}\right), \quad (17)$$

where

$$\begin{aligned} D_1 &= TN_0, \\ D_2^{\mathrm{L}} &= \left(2\lambda_{\mathrm{t}}^{\mathrm{L}}(m)+\lambda_{\mathrm{s}}(1-\exp\left(-\lambda_{\mathrm{t}}^{\mathrm{L}}(Q)W_{\mathrm{s}}\right))\right)\varrho(T,\alpha_{\mathrm{L}}), \\ D_2^{\mathrm{N}} &= \left(2\lambda_{\mathrm{t}}^{\mathrm{N}}(m)+\lambda_{\mathrm{s}}(1-\exp\left(-\lambda_{\mathrm{t}}^{\mathrm{N}}(Q)W_{\mathrm{s}}\right))\right)\varrho(T,\alpha_{\mathrm{N}}), \end{aligned} \quad (18)$$

and

$$\varrho(T,\alpha) = \int_1^{\infty}\frac{1}{1+T^{-1}\mu^{\alpha}}d\mu. \quad (19)$$

The deconditioned coverage probability for a vehicle on mth lane $P_{\mathrm{c}}(m,T)$ is

$$P_{\mathrm{c}}(m,T) = \int_0^{\infty} p_{\mathrm{c}}(v,m,T)f(m,v)dv, \quad (20)$$

and $f(m,v)$ is the probability density function (PDF) of the associated link gain, which can be derived from the CDF in Lemma 2.

D. LT of typical street interference

Considering the blockage from vehicles, the LT of the total interference is the multiplication of the two individual LT of blocked and unblocked BSs. By neglecting the distance between the receiver and the roadside, the LT of the total interference from LOS BSs on the typical street becomes

$$\mathcal{L}_1\left(\frac{T}{v}\right) = \exp\left(-2\lambda_{\mathrm{t}}^{\mathrm{L}}(m)\varrho(T,\alpha_{\mathrm{L}})v^{-\frac{1}{\alpha_{\mathrm{L}}}}\right) \times \exp\left(-2\lambda_{\mathrm{t}}^{\mathrm{N}}(m)\varrho(T,\alpha_{\mathrm{N}})v^{-\frac{1}{\alpha_{\mathrm{N}}}}\right), \quad (22)$$

which resembles the result in [9], except that we incorporate the interference from blocked BSs in analysis.

E. LT of cross streets interference

We then make the following assumption of the BSs inside the LOS region, to maintain tractability of analysis.

Assumption 5. *There is at most one BS in each LOS region of the cross street, i.e., we only consider the interference coming from the closest LOS BS on cross streets.*

Assumption 5 considers only the closest LOS BS inside the LOS region on the cross street. This is reasonable because when the cross street is far away from the receiver, i.e., x turns relatively large, in which case the LOS region becomes very small, $L(x)\to\frac{W_{\mathrm{s}}}{2}$. From the previous demonstration, we can derive the LT of the interference from LOS BS on cross streets in (21) (see top of next page).

In (21), (a) follows by considering all the BSs inside the LOS region and approximating the Euclidean distance of a BS on a cross street by just the horizontal Manhattan distance. (b) is based on approximating the LOS region area by $L(x)=W_{\mathrm{s}}/2$, even though the actual LOS region is larger than this,

$$\mathcal{L}_2\left(\frac{T}{v}\right) = \exp\left(-2\lambda_{\rm t}^{\rm L}(Q)\lambda_{\rm sv}\int_{v^{-\frac{1}{\alpha_{\rm L}}}}^{\infty}\left(\int_0^{\min\left\{\sqrt{\bar{r}_{\rm L}^2-x^2},L(x)\right\}}\left(\frac{1}{1+\frac{v}{T}\left(x^2+y^2\right)^{\frac{\alpha_{\rm L}}{2}}}\right)\exp\left(-2\lambda_{\rm t}^{\rm L}(Q)y\right)dy\right)dx\right)$$
$$\overset{(a)}{\approx}\exp\left(-2\lambda_{\rm t}^{\rm L}(Q)\lambda_{\rm sv}\int_{v^{-\frac{1}{\alpha_{\rm L}}}}^{\infty}\frac{1}{1+\frac{v}{T}x^{\alpha_{\rm L}}}\left(\int_0^{L(x)}\exp\left(-2\lambda_{\rm t}^{\rm L}(Q)y\right)dy\right)dx\right)=\exp\left(-\lambda_{\rm sv}\int_{v^{-\frac{1}{\alpha_{\rm L}}}}^{\infty}\frac{1-\exp\left(-2\lambda_{\rm t}^{\rm L}(Q)L(x)\right)}{1+\frac{v}{T}x^{\alpha_{\rm L}}}dx\right)$$
$$\overset{(b)}{\approx}\exp\left(-\lambda_{\rm s}\left(1-\exp\left(-\lambda_{\rm t}^{\rm L}(Q)W_{\rm s}\right)\right)\int_{v^{-\frac{1}{\alpha_{\rm L}}}}^{\infty}\left(\frac{1}{1+\frac{v}{T}x^{\alpha_{\rm L}}}\right)dx\right)=\exp\left(-\lambda_{\rm s}\left(1-\exp(-\lambda_{\rm t}^{\rm L}(Q)W_{\rm s}\right)\varrho(T,\alpha_{\rm L})v^{-\frac{1}{\alpha_{\rm L}}}\right), \tag{21}$$

but $L(x)\to\frac{W_{\rm s}}{2}$, with x becomes large. The key idea behind the approximation $\mathcal{L}_2$ is: i) for a cross street, see if there is BS in the approximated LOS region; ii) if there is, put a *virtual* BS at the corner of the cross street. This is equivalent to adding an extra set of BSs on the typical street, with intensity $\lambda_{\rm s}\left(1-\exp\left(-\lambda_{\rm t}W_{\rm s}\right)\right)$. Hence, the LT for total interference becomes

$$\mathcal{L}_2\left(\frac{T}{v}\right) = \exp\left(-\lambda_{\rm s}\left(1-\exp(-\lambda_{\rm t}^{\rm L}(Q)W_{\rm s}\right)\varrho(T,\alpha_{\rm L})v^{-\frac{1}{\alpha_{\rm L}}}\right)$$
$$\times\exp\left(-\lambda_{\rm s}\left(1-\exp(-\lambda_{\rm t}^{\rm N}(Q)W_{\rm s}\right)\varrho(T,\alpha_{\rm N})v^{-\frac{1}{\alpha_{\rm N}}}\right). \tag{23}$$

It can be seen that the result has a very concise expression, which is shown to be tight as well in numerical results.

V. Numerical results

We verify the results of the BS association in Fig. 3. In Fig. 3, we compare the distribution of the associated path gain. The gap between the distribution considering only the BSs on the typical street and that including the cross street BSs is small, as a result, in the analysis of coverage probability, we assume the vehicle is always connected to either a LOS or NLOS BS on the typical street.

Fig. 4 plots the numerical and approximate analytic coverage probability considering only the interference of the typical streets and BSs on cross streets in LOS region. Comparisons are made with different lane width, which are differentiated as blue, red and black curves with $W_{\rm L}=3,5$ and 7. First, the approximate analytic result is fairly tight with the exact coverage probability. Second, increasing lane width mainly has two effects: i) larger distance from the roadside with BSs which reduces both channel path gain and interference; ii) an increasing size of the LOS region on cross streets and larger interference. The cross street interference does not have great impacts on the coverage probability, even if with larger street width.

Fig. 5 compares different levels of blockage effects on throughput. Throughput here is defined by $\mathcal{R}(T)=\log_2(1+T)P_{\rm c}(T)$. It can be seen that blockage effects actually can improve the coverage a little bit, due to the reduced interference introduced, however, the blockage effects in general have minor effects on the coverage probability, even if with a very large blockage intensity. This illuminates an important conclusion that in multiple-lane vehicular networks, unlike the V2V blockage [2] or urban cellular blockage [4], blockage among vehicles on different lanes with V2I is not significant, even in urban microcells where BSs are usually deployed at roadside with relatively low height. This is mainly because the vehicle of V2I in a multi-lane scenario actually only have one-dimensional blockers. This is different from the blockage effects in V2V or urban cellular network, which have dense users/blockers and more prominent blockage effects in a *radial* type two-dimension geometry.

Fig. 6 compares the coverage probability under different network intensities. Larger BS intensities increase interference and makes the network interference limited, while coverage is degraded with denser streets due to increased interference of cross streets.

VI. Conclusion

This paper proposed a tractable framework to analyze the blockage and coverage in urban mmWave vehicular networks. It is shown that the coverage probability is mainly affected by the BSs on the typical street, while those on the cross streets with LOS visibility have negligible effects on performance. In a dense streets network, deploying dense BSs cannot improve coverage. Also, the blockage effects in multi-lane vehicular networks of V2I are insignificant. Detailed modeling of blockage effects due to vehicles in the V2I scenario, to include diffraction and shadowing losses, if any, and corresponding coverage analyses are interesting directions for future work.

VII. Acknowledgment

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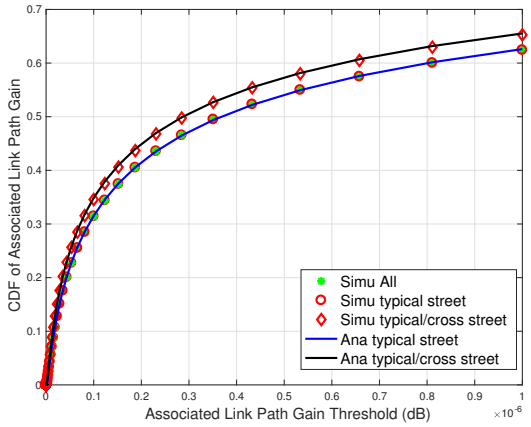

Fig. 3: The comparison between the analytical and numerical results of the CDF of the associated link path gain. The green star, red circle and red diamond are respectively the association distribution considering all association cases, the association with the BSs with LOS visibility and the association only with the LOS BS typical street.

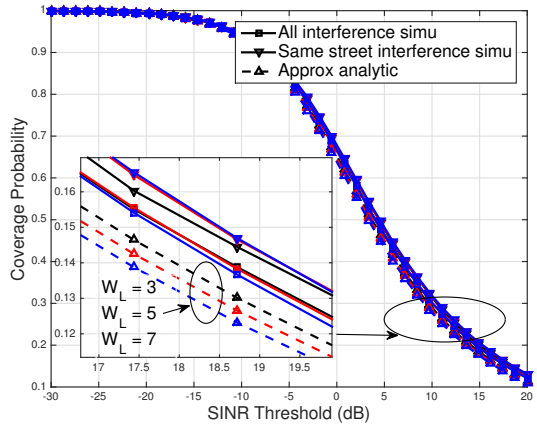

Fig. 4: Comparison of coverage probability in terms of considering all interference, same street interference and analytical approximation. Black, red and blue curves respectively characterize coverage probability with the lane width as $W_{\mathrm{L}} = 3, 5, 7$.

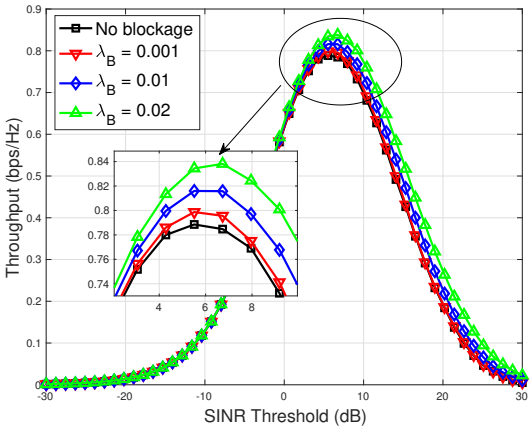

Fig. 5: Red, blue, green curves respectively represent different blockage vehicle intensities $\lambda_{\mathrm{B}} = 0.001, 0.01, 0.02$. The comparison is made among throughput without considering blockage and with different blockage intensities.

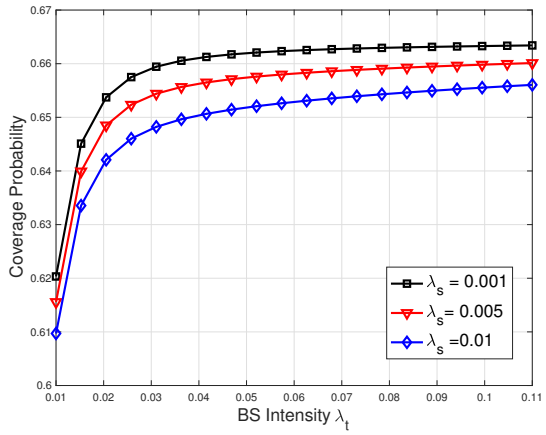

Fig. 6: Comparison of coverage probability under different BS intensities with different street setting as $\lambda_{\mathrm{s}} = 0.001, 0.005, 0.01$.

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