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Efficient Resource Allocation for Interference Management in 5G Mm Wave Vehicular Networks

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Abstract Vehicular communication underlaying cellular infrastructure has the advantage to provide shorter distance between devices, thereby reducing path loss and help improve transmission reliability. However, due to complicated communication environment and high mobility, providing efficient and reliable vehicular transmission to satisfy different requirements has become challenging. One of such challenges is interference caused by other networks to vehicle users, which invariably impacts the quality of service. In this paper, we propose a robust spectrum and power allocation scheme that takes into account fast-varying components of the channel state information (CSI) and environmental conditions with less complexity. In addition, a model to capture and address the effect of line of sight/non-line of sight (LoS/NLoS) interference resulting from co-located infrastructure in urban vehicular scenario is developed. Subsequently, we derive an expression for the outage probability to evaluate the reliability requirements, based on the slow fading channel information available at the base station. Simulation results show an improved performance in terms of capacity and coverage of the network.

Keywords 5G, CSI, interference management, mmWave, vehicular networks

1. Introduction

Recent advancement in information and communication technology (ICT) has necessitated the envisioned 5G technology to accommodate an unprecedented heterogeneous and ultra-dense communication environment. The great potentials of vehicular communications to support intelligent transportation system (ITS), ensure reliability and provide various safety applications on our roads have continuously triggered hot research focus in recent years [1-2]. The concept of ITS, as shown in Fig. 1, involves communication among vehicles, called vehicle-to-vehicle (V2V) communication, and between vehicles and the infrastructure or road-side unit (RSU), termed vehicle-to-infrastructure (V2I or V2R) communication [3-4]. However, despite the vast benefits, there are several challenges faced by vehicular communication such as traffic safety and congestion, which greatly affects the capacity requirements, especially in urban settings with high vehicle density. In addition, high urban vehicular density often leads to serious competition for the available network capacity by various applications and data-driven devices. Similarly, high vehicle mobility can restrict connectivity which can in turn delay important information delivery. Vehicular communication underlaying cellular infrastructure has the advantage to provide shorter distance between devices, thereby reducing path loss and help improve transmission reliability [5]. However, due to complicated communication environment and high mobility, providing efficient and reliable vehicular transmission to satisfy different requirements has become challenging. One of such challenges is interference caused by other networks to vehicle users, which invariably impacts the quality of service of some vehicular applications.

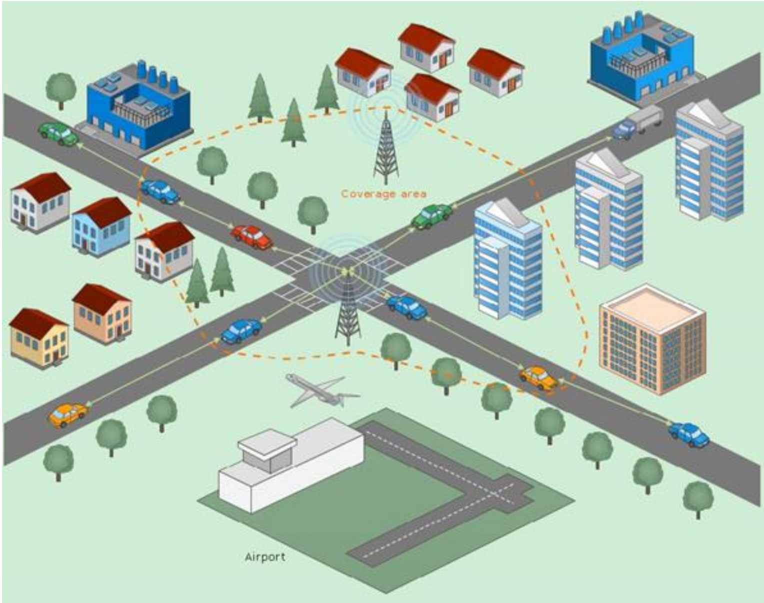

Figure 1: Vehicular communication in urban cellular networks

The interference is more severe when, unavoidably, V2V and cellular users reuse the same spectrum within the network [6]. Hence, to realize the goal of achieving enhanced system performance, there is urgent need to design an efficient algorithm that jointly considers spectrum utilization and power control specifically for interference mitigation, while matching geographical information with data queue dynamics. Although, a lot of work has been done in the area of radio resource management for both cellular and vehicular communication [7-9]. To date, none of the existing literature has been able to achieve interference reduction in vehicular networks through blended delay communication, dynamic links, CSI availability, as well as LoS/NLoS effect in the resource allocation optimization and performance analysis, respectively. Motivated by the aforementioned shortcomings, this paper proposes a robust spectrum and power allocation scheme that opposes the general assumption that global CSI is unavailable at all network entities, and takes into account fast-varying and environmental conditions with less complexity. The main contribution of this paper is highlighted below:

- Exploit the tractability of stochastic geometry on Poisson point as a realistic representation of urban streets to analyze the coverage of both cellular and vehicular UEs.
- Develop a model to capture and address the effect of LoS/NLoS interference resulting from co-located infrastructure in urban vehicular scenario.
- Derive closed-form expressions to maximize capacities of all V2V/V2I links.
- Derive an expression for the outage probability to evaluate the reliability requirements, based on the slow fading channel information available at the BS.

The structure of the rest of this paper is summarized as follows: Related literature are described in the next section followed by theoretical analyses of vehicular network model. Simulation results and discussion are presented next. Finally, the conclusion and future work areas are presented.

2. Related Work

With vehicular network constituting a special family of Mobile Ad-hoc Networks (MANETs), a lot of efforts have been targeted at solving many contending issues so as to derive maximum benefit of V2V communications. Vehicles use different wireless access technologies to communicate among themselves and with the nearby infrastructure or RSU. Either short range, such as Wi-Fi or long-range wireless access in vehicular environment (WAVE) technology may be used as the wireless technologies for cellular networks, although both technologies offer collective overall capacity if they co-exist. The authors in [10-11] formulated resource allocation problem in multi-user OFDM system and incorporated it into security platform of physical layer. Furthermore, full CSI is assumed to be available at the BS in the existing resource allocation problems [12-13]. However, this assumption may be invalid due to the difficulty in obtaining full CSI of the rapidly changing vehicular network topology. Thus, the resource allocation results take a non-negligible time to obtain, hence creating more challenges for channel modeling in vehicular networks [14] addressed this problem through power allocation formulation that jointly incorporates chance constraints and Non Orthogonal Multiple Access (NOMA) scheme. The objective of this approach is to improve spectrum efficiency and limit cross-tier interference.

Recently, a lot of attention has been focused on mmWave band as a way to solve the problem of scarce spectrum utilization [13, 16-17]. In pursuant of this, a typical urban street environment was modeled as a 3-dimensional Manhattan Poisson Line Processes (MPLP) in [17] using stochastic geometry in combination with mmWave-specific channel model. The model considered variations in the propagation environment and LOS/NLOS interference effects. Using the same model, the work in [17] was extended further in [18] to maximize the ergodic capacity of CUEs by deriving a closed form expression that considers QoS requirements for both V2I and V2V links. However, the work in [13] proposed a blended swarm intelligence and matching theory to efficiently and dynamically pair vehicles for transmission and reception beam widths optimization. In the paper, Queue State Information (QSI) and CSI were jointly considered when establishing V2V links. Finally, the authors in [19] formulated a resource allocation optimization in Device-to-Device (D2D)-overlaid vehicular communications. The paper accounted for fast variation in channel condition occasioned by high mobility nature of D2D overlaying vehicular networks. This is to ensure that the outage probability of the received signal is prevented from exceeding a certain threshold value. Also, the authors exploited the small variation in large-scale fading signal present in wireless channel of highway scenario to perform resource allocation and spectrum sharing, as against common formulations based on full knowledge of CSI at the BS.

3. System Model

Consider an urban area vehicular communication network consisting of M CUEs and Kpairs VUEs as shown in Fig. 2. Denote the corresponding sets by $\mathcal{M} = \{1,2, \dots M\}$ and $\mathcal{K} = \{1,2, \dots K\}$, respectively and assume orthogonal RB allocation for the CUE tobe performed by any reasonable scheduling scheme. In addition, two homogeneous PoissonPoint Processes (PPP) are generated as Φ_x and Φ_y. Also, multiple VUEs can be paired witha particular CUE simultaneously for RB sharing [20], resulting in interference scenario depicted in Fig. 2. Assume a flat fading and

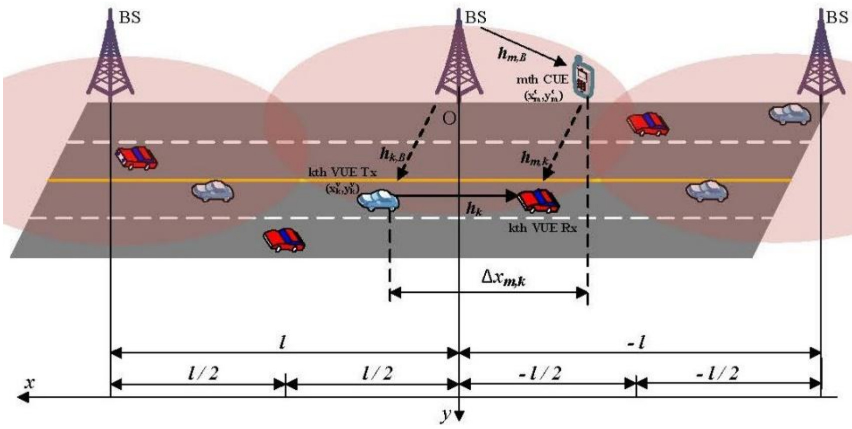

Figure 2: Interference scenario between V2V and V2I links in vehicular communication topology

narrow-band channel, the average power gain of the channel between the mth CUE and the BS can be expressed as

$$h_{m,B} = L_{m,B} D_{m,B}^{-\delta} S_{m,B} g_{m,B} \triangleq \alpha_{m,B} g_{m,B} \quad (1)$$

where $g_{m,B}$ denotes the small-scale fast fading component, $L_{m,B}$represents the path loss coefficient, $D_{m,B}^{-\delta}$D is the distance between the mth CUE and the BS, δ is the path lossexponent. The path loss and shadowing effect of all links are incorporated in $\alpha_{m,B}$to formthe large scale fading components of the channel, while $S_{m,B}$ is the log-normal shadow fadingwith distribution [21]

$f_{S_{m,B}}(S) = \frac{\xi}{\sqrt{2\pi\sigma_s S}} exp\left[\frac{(10log_{10}s)^2}{2\sigma_s^2}\right]$ (2)

where $\xi = 10/ln10$. The BS has knowledge of this information since it is dependent onusers' locations and also vary on a slow scale. For $\alpha_{m,B}$ and $\alpha_{k,B}$, i.e., the links betweenCUEs/VUEs and the BS, the information will be estimated by the BS, while the BS receivesperiodically the parameter reports estimated at the VUE receiver based on CSI feedbackinterval Υ for α_k and $\alpha_{m,k}$,i.e., links between vehicles. The fast fading components of the channel variation over the period $\Upsilon$with quantity φ being the channel correlation betweentwo consecutive time slots can be modelled using the Jakes' model for fading channel as [22]

$\varphi = \varepsilon_0(2\pi f_d \Upsilon)$ (3)

where $\varepsilon_0(\cdot)$ denotes the zeroth-order Bessel function and $f_d = v\, f_c/c$ represents the maximumDoppler frequency with f_c being the carrier frequency, v is the vehicle speed and $c = 3 \times 10^8$m/s.

Pathloss model is used in cellular networks to determine LoS and NLoS links, since transition between LoS/NLoS links is common in urban setting due to high density of streets and skyscrapers. In this case, estimating pathloss through Euclidean distance calculation only works for randomly oriented buildings, but not V2I links where interference may result fromco-located infrastructure on the same street [23]. Thus, PPP helps to characterize correlated shadowing effects in urban buildings. Therefore, to account for street geometry and capture the effect of blockage and shadowing due to buildings in an urban setting, we consider the following:

- In urban scenario, there are different segments.
- Pathloss on different segments are added up
- Assume there are N segments in total, along the propagation paths, then there are(N-1) corners where signals change direction.

Hence let,

δ_j - represent pathloss exponent of segment j.

β - represent loss at the corner of $j$and $(j+1)$ segment, which is identical at different corners.

δ_L - denote pathloss exponent shared by LoS segments on different streets

δ_N - be the pathloss exponents for NLoS segments.

The pathloss added by extra beamforming gain in the antenna model at the BS can be expressed as [17]

$$\Gamma_{\text{dB}} = 10\left(\delta_L \log_{10} l_1 + \delta_N \sum_{j=2}^{N} \log_{10} l_j\right) + (N-1) \quad (4)$$

Thus, following from Eq. (1), the corresponding channel gain between CUE m and VUE k, VUE k and the BS and VUE pairs are, respectively expressed as

$h_{m,k} = L_{m,k} D_{m,k}^{-\delta} S_{m,k} g_{m,k} \triangleq \alpha_{m,k} g_{m,k}$ (5)

$h_{k,B} = L_{k,B} D_{k,B}^{-\delta} S_{k,B} g_{k,B} \triangleq \alpha_{k,B} g_{k,B}$ (6)

$h_k = L_k D_k^{-\delta} S_k g_k \triangleq \alpha_k g_k$ (7)

Using the base station association rule on the urban street topology, then denote by $\lambda_{m,B}^2$ the set of LoS link with distance $x_{m,B}^2$ from the BS to$m$-th CUE, $\lambda_{m,B}^3$ the set of LoS/NLoS links with distances $x_{m,B}^3$ and $y_{m,B}^3$, and $\lambda_{m,B}^1$ the set of distances $x_{m,B}^1$,$y_{m,B}^1$ and $z_{m,B}^1$. Hence, LoS and NLoS segment path gains are, respectively, expressed as

$u_L(x) = G(x)^{-\delta_L}andu_N(x) = c(x)^{-\delta_N}$ (8)

where G is the beamforming antenna gain of the BS added only to the LOS segment pathloss, being the closest and first path to the BS. Also, the term $c = 10^{-\Delta/10}$ represents the cornerloss included in the NLOS propagation segment. The signal-to-interference-plus-noise ratio (SINR) of the link from m-th CUE to the BS is given by

$\gamma_m^c = \frac{P_m^c h_{m,B}}{\sigma^2 + I_T}$ (9)

where $I_T = \sum_{\substack{k=\mathrm{K} \\ x^2_{m,B} \in \lambda^2_{m,B}}} \rho_{m,k} P^v_m h_{k,B} u_L(x^2) + \sum_{\substack{k=\mathrm{K} \\ (x^3_{m,B}, y^3_{m,B}) \in \lambda^3_{m,B}}} \rho_{m,k} P^v_m h_{k,B} u_N(x^3) u_L(y^3)$

$+ \sum_{\substack{k=\mathrm{K} \\ (x^1_{m,B}, y^1_{m,B}, z^1_{m,B}) \in \lambda^1_{m,B}}} \rho_{m,k} P^v_m h_{k,B} u_N(x^1) u_N(y^1) u_L(z^1)$

Note that I_T is the sum LOS and NLOS of power received from the network, called totalinterference. Similarly, SINR at the BS for the link between k-th VUE pair is

$$\gamma^v_k = \frac{P^v_k h_k}{\sigma^2 + \sum_{m \in \mathrm{M}} p_{m,k} P^c_m h_{m,k}} \quad (10)$$

whereP^c_m and P^v_k represent transmit powers of the m-th CUE and k-th VUE, respectively,σ^2 is the channel's AWGN and $\rho_{m,k} \in \{0,1\}$ denotes the spectrum allocation indicator, suchthat

$$\begin{cases} \rho_{m,k} = 1, & \text{VUE pair } k \text{ reuses the spectrum of the } m\text{th CUE} \\ \rho_{m,k} = 0, & \text{otherwise} \end{cases} \quad (11)$$

It is always impossible in highway setting for the BS to estimate the information containing small scale fading values due to very high vehicular speeds. This compels the BS to assume average values for the small scale fading and full CSI of large scale fading. Thus, the capacity of mth CUE at acertain position can be expressed as

$$C^c_m = \mathbb{E}_g[log_2(1 + \gamma^c_m)] \quad (12)$$

Similarly, the capacity of kth VUE pair at a certain position is

$$C^v_k = \mathbb{E}_g[log_2(1 + \gamma^v_k)] \quad (13)$$

where the expectation $\mathbb{E}_g[.]$ is measured with respect to the fast fading distribution. Inurban vehicular network settings, BSs are deployed at street level, where building blockagesare considered as the main source differentiating LOS and NLOS links. In this manner, NLOS BSs constitute less benefit for association, hence ultra-dense deployment of BSs does not enhance coverage. Thus, pathloss model with a LOS probability function based on Euclidean distance are often used to determine whether a link was LOS or NLOS. However, this works well for randomly oriented buildings, but does not properly model V2I networks where strong LOS interference may result from infrastructure co-located on the same street. Therefore, we assume a spatially consistent pathloss model as a function of both the street orientation and the absolute location of the BS and UE. Hence, let a BS be positioned at the origin marked O and construct X axis in the direction of the road with Y axis along the horizontal plane, perpendicular to X, as depicted in Fig. 2. Denote the coordinates of mth CUE and transmitter of the kth VUE on the plane as (x^c_m, y^c_m) and (x^v_k, y^v_k), respectively. For simplicity, we consider a single lane such that each vehicle travels on the same direction, hence (y^c_m) and (y^v_k) remain unchanged. The midpoint between two nearest BSs constitutes the access period given as the path from $(\frac{-l}{2}, 0)$ to $(\frac{l}{2}, 0)$. The CUE maintains connection with the BS at this period after which it switches to another BS. At this instance, the spectrum of every CUE can either be reused by a VUE or not, according to Eq. (11).

4. Coverage Analysis

As shown in the previous analyses, the CUEs and VUEs exchange predefined sets of resources upon transmission requests during semi persistence scheduling period. Since latency and reliability are key requirements, scheduling is set at the same order of latency requirement, thereby removing unwanted exchange of signal in each slot. Hence, the BS helps to reduce resource collision by performing holistic spectrum allocation, taking into consideration the position information supplied by each CUE/VUE, which are updated at the onset of scheduling process. Concurrently, human-to-human (H2H) traffic should be guaranteed while attempting to achieve continuous communication requirement in mobility-prone environment for message transmission efficiency. Equipped by this information, the vehicular network is challenged by co-channel interference due to dense topology, spectrum sharing among various users and time variant environment, caused by mobility. In this section, the impact of co-channel interference on network capacity is analyzed. Also, the effect of LoS and its complementary NLoS on network coverage will be presented. The coverage probability can be derived under the condition that the received SINR is greater than a predefined threshold θ, for a typical user located at the origin O.

Using stochastic geometry as a tractable means of analysis, the coverage probability p_c , taking into accountvehicular orientation and the system model derived in Section 3 can be expressed as

$$p_c = \mathrm{P}[\gamma_m^c > \theta] = \mathrm{P}\left(\frac{P_m^c h_{m,B}}{\sigma^2 + I_T} > \theta\right) \tag{14}$$

Obviously, the coverage probability defined in Eq. (14) can be viewed as an alternative interpretation of the complementary cumulative distribution function (CCDF) of the SINR, γ_m^c and γ_k^v derived in Eq. (9) and Eq. (10), respectively. Extracting the small scale components $g_{m,B}$ of the channel gain $h_{m,B}$ between mth CUE and BS, and putting $I_T = I_{LOS} + I_{NLOS}$ yields

$$p_c = \mathbb{E}_{I_{LOS}+I_{NLOS}}\left[P_r\left(g_{m,B} > \frac{\theta(\sigma^2 + I_{LOS} + I_{NLOS})}{P_m^c h_{m,B}}\right)\right] \tag{15}$$

By applying the properties of small scale Rayleigh fading and assuming all links experience independent and identically distributed (i.i.d) fading where $g_{m,B} \overset{i.i.d}{\sim} \exp(1)$ with unit mean,we have

$$p_c = e^{(-q\sigma^2)}\mathbb{E}_{I_{LOS}+I_{NLOS}}\left[e^{(-q(I_{LOS}+I_{NLOS}))}\right] \tag{16}$$

where $q = \frac{\theta}{P_m^c h_{m,B}}$. Thus, transforming Eq. (16) using the properties of Laplace transform yields

$$p_c = e^{(-q\sigma^2)} \prod_{j=1}^{N_{LOS}} \underbrace{\mathrm{L}_{I_{j,LOS}}(q)}_{a} \prod_{j=1}^{N_{NLOS}} \underbrace{\mathrm{L}_{I_{j,NLOS}}(q)}_{b} \tag{17}$$

Although, there exists two possibilities, namely: random and clustered distribution for modeling vehicles orientation, depending on the type of setting, i.e. urban or highway environment. However for simplicity, we assume random distribution for both urban and highway settings in this work. Under this assumption, the first part (a) of Eq. (17) can be extended as

$$\mathrm{L}_{I_{j,LOS}}(q) = \mathrm{E}_{I_{j,LOS}}\left[e^{(-q)I_{j,LOS}}\right] = \mathrm{E}_{I_{j,LOS}}\left[e^{\left(-q\sum_{k\in\Phi} P_k^v h_{j,k} G(x)^{-\delta_L}\right)}\right]$$

$$= \mathrm{E}_{I_{j,LOS}}\left[\prod_{k\in\Phi} \mathrm{E}_h e^{\left(-qP_k^v h_{j,k} G(x)^{-\delta_L}\right)}\right] = \mathrm{E}_{I_{j,LOS}}\left[\prod_{k\in\Phi} \frac{1}{1 + qP_k^v h_{j,k} G(x)^{-\delta_L}}\right] \tag{18}$$

Similarly, the NLOS interference in the second part (b) of Eq. (17) can be derived in the same manner by replacing pathloss for the NLOS segment with$cx^{-\alpha N}$, previously defined in Eq. (8).

5. Result and Discussion

In this section, simulations were performed to evaluate the effectiveness of the proposed resource and power allocation scheme for the urban vehicular network. In our simulation, vehicle UEs are dropped on the road according to Spatial Poisson Process. The vehicle position is updated every 100 ms in the simulation while the vehicle density is determined by the vehicle speed. For urban case, ISD of BSs is given as 500 m and the wrap around model is used according the 3GPP specification [24]. In addition, the channel model follows the WINNER II standard channel model where both V2I and V2V links assume Rayleigh fading and Log-normal shadowing distribution, with 8 dB and 3 dB shadowing standard deviation, respectively.

Fig. 3 illustrates the sum ergodic capacity trend against the feedback time for different values of transmission powers in highway scenario. It can be seen that the capacity is maximized up to ϒ = 0.5 ms before a gradual decline in the system capacities for thevarious values of transmit power. In addition, the insensitivity of the capacity to the CSIfeedback period at low SNR values as against higher values of SNR can be seen. A closer look at the figure shows feedback period point for optimal capacity to be 0.5 ms after which the system capacity suffers degradation gradually as the feedback period increases.

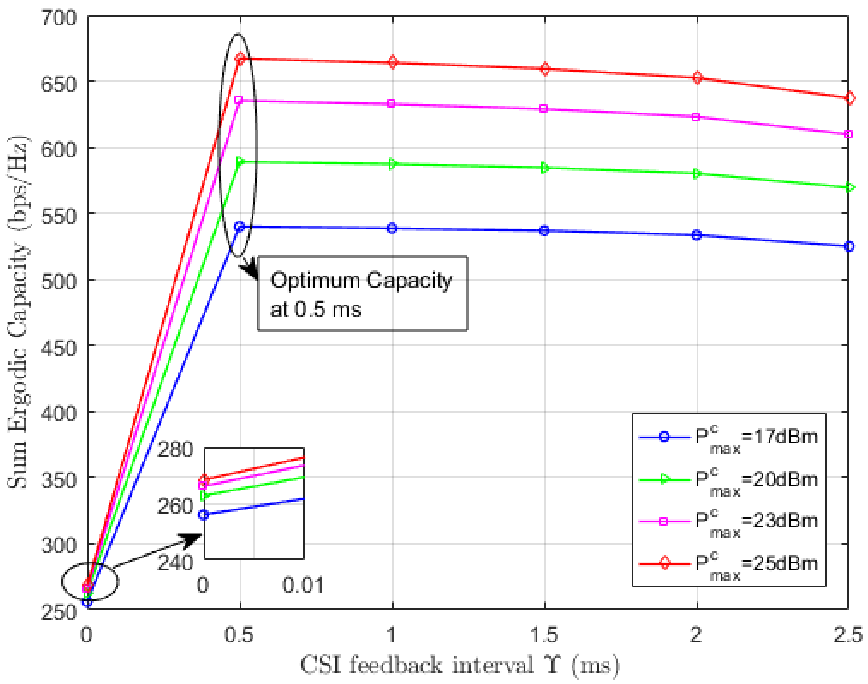

Figure 3: The effect of feedback time ϒ on the sum ergodic capacity with varying valuesof maximum transmit power for V2V and V2I links.

Hence, as the feedback time grows, the more uncertainty is introduced into $\alpha_k$and $\alpha_{m,k}$, being the links between vehicles. This promptsthe BS to control the transmit powers of CUEs in order to favour V2V links in meetingtheir reliability requirements, and to protect the V2V against the interference caused by the CUEs. Moreover, at 25 dBm transmit power, the behaviour of the capacity is slightly different from the other three values of transmit power, i.e., 17 dBm, 20 dBm and 23 dBm. While at 17 dBm, the ergodic capacity maintains a relatively constant value after 0.5 ms feedback time when P^{c}_{max} = 23 dBm. As shown, the capacity starts to fall at ϒ = 2 ms, particularly for higher transmit power, due to the overhead created by regular exchange ofCSI information between CUEs/VUEs and the BS.

Fig. 4 shows the CDF of the SINR for V2V links simulated under ϒ = 0.5 ms andϒ = 1.0 ms. The two values are carefully chosen to capture and analyze the capacity at optimum point in Fig. 3 and the behaviour beyond this point. As expected, the performance at ϒ = 1 ms is slightly higher than ϒ = 0:5 ms by 0.8 dB. The performance gap is due to the availability of CSI atthe receiver which enables proper cancellation of interference. Considering the importance ofprompt channel feedback on latency and reliability in vehicular networks, the less feedback value is expected to provide enhanced capacity. However, in this case, recurrent exchange of channel information may lead to unnecessary bottlenecks which will reduce the overall system capacity.

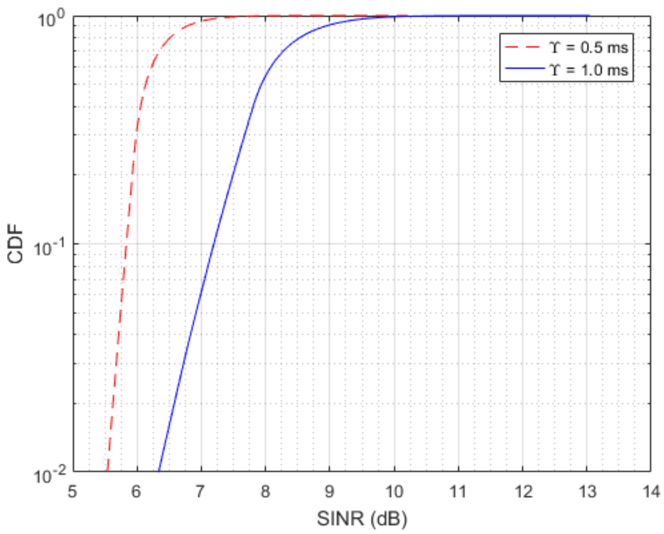

Figure 4: CDF plot of SINR for V2V links with two values of feedback duration ϒ = 0.5ms and ϒ = 1.0 ms

Fig.5 demonstrates the impact of traffic density and vehicle mobility on successful vehicle connectivity using communication range of 50 m and 100 m from a specific target. The choice of the two range values allows the simulation to capture the freeway car following model and lane changing model in urban settings. As can be seen in the case of 50 m communication range, the average number of vehicle connectivity increases gradually as the traffic density also increases. This is clearly due to the vehicles moving closer to each other, thereby causing congestion in the traffic. Hence, the average vehicular connectivity increases linearly with the traffic density. However, a slight drop in vehicle connectivity can still be noticed when the traffic volume is high. This is partly due to the effect of building blockages and change in signal direction along the propagation paths from LoS to NLoS, often experienced in urban environment. The LoS/NLoS segment path gains given in Eq. (8) and the use of PPP to capture shadowing effect helps to reduce this effect. On the other hand, when the communication range increases to 100 ms, it can be observed that more vehicle connectivity is experienced.

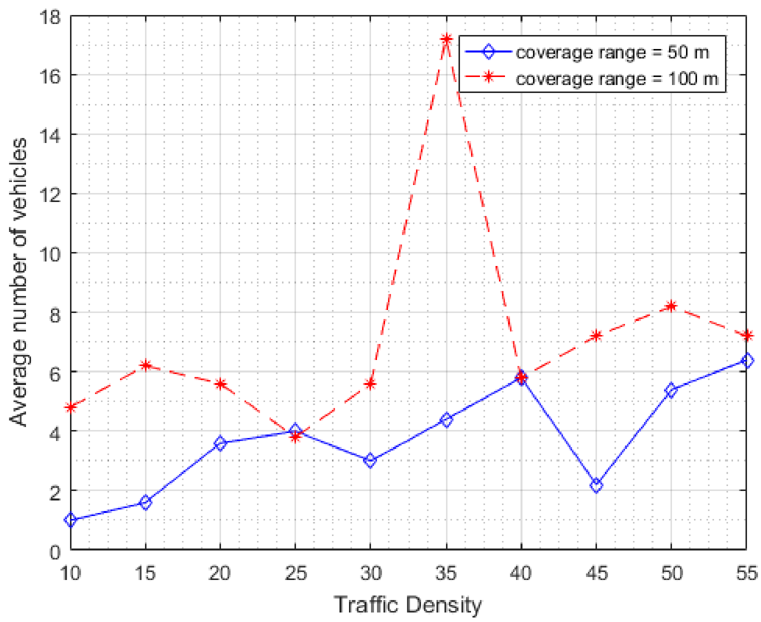

Figure 5: Connectivity plot for communication range

6. Conclusion

In this paper, we exploit the tractability of Poisson Point Processes and proposed a mathematical framework to model an urban-type vehicular communication network using stochastic geometry. The model takes into account presence of correlated buildings and the resultant shadowing effects, hence providing excellent basis for tractable analysis. In this approach, locations of BSs and cellular users are modeled on a two-dimensional plane as Poisson point processes so as to derive the coverage probability of a cellular user. Simulation results showed a better performance in our approach compared to related works.

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