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Optimal Power Allocation and Capacity Analysis for D2D-Enabled Vehicular Communications

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Abstract**:** ***Wireless Communication is important to recover transmitted information by accommodating reliable Information flow to allow safety, mobility and environmental applications. In cellular communication resources are shared with the users to improve spectral reuse and enhance channel capacity. Device-to-Device (D2D) communication has become a promising technology for wireless engineers to optimize the network performance. In vehicular environment, the design of resource allocation schemes for D2D-enabled networks need to be properly addressed because of the fast channel variations due to high mobility.***

In this work, Radio Resource Management (RRM) for D2D-based V2X (Vehicle to Everything) communications including both vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communication are implemented. Power is allocated based on slowly varying large-scale fading information of wireless channels of LTE standard

The objective is to maximize the ergodic capacity of V2I connections by ensuring reliability for each V2V link. Sum ergodic capacity of all V2I links is first taken as the optimization goal to maximize the general V2I link throughput. Minimum ergodic capacity maximization is then taken into consideration to offer a more uniform capacity performance throughout all V2I links. Various algorithms that gives optimal power allocation are proposed and compared. Here, the capacity maximization between highway areas and urban areas are compared and concluded that capacity maximization will be higher in urban areas then on highways.

Keywords **:** ***Device to Device (D2D); Long-Term Evolution (LTE); Vehicle to Everything (V2X); Vehicleto Vehicle (V2V); Vehicle to Infrastructure (V2I); ergodic capacity, , power allocation.***

I. INTRODUCTION

Vehicle-to-vehicle (V2V) communications have become a significant technology for improving transportation services and reducing road casualties. Due to vital applications in the traffic safety, the necessities for the V2V communication links are often very stringent, i.e., the millisecond of end to-end latency and nearly 100% of reliability[1] The 3rd Generation Partnership Project (3GPP) enables highly efficient and reliable vehicular communications in future generation wireless networks [2]. As illustrated in Fig. 1, Information, entertainment applications and traffic efficiency messages generally require frequent access to the Internet or remote servers for media streaming, content sharing, etc. Hence are ideally supported by the high-capacity vehicle-to-infrastructure (V2I) links involving considerable amount of data exchange. Meanwhile, safety-critical information, such as cooperative awareness messages (CAMs) and decentralized environmental notification messages (DENM) [3], leads to spreading safety related messages among surrounding vehicles either in a periodic or event triggered way. Hence, it is naturally supported by the vehicle-to-vehicle (V2V) links, which impose strict reliability and timeliness requirements.)

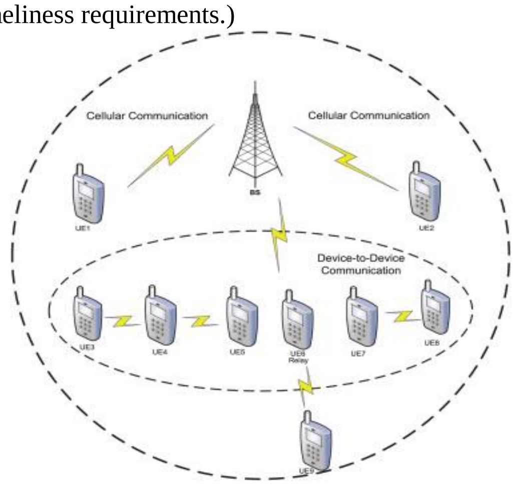

Fig.1. D2D-enabled vehicular communications for both V2I and V2V links.

A defacto standard IEEE 802.11p based vehicular communications have been widely studied in recent years. However in 802.11p carrier-sense based multiple access scheme faces great challenges in guaranteeing quality-of-service (QoS) requirements of V2X communications, especially for heavy traffic load [4].

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As an alternative QoS-aware resource allocation have a sufficient potential, in the cellular assisted vehicular communications which satisfies the requirements of QOS parameters of
different types of links, where the V2V and V2P communications are performed based on the cellular assisted device-to-device (D2D) technique [5].

In D2D communication the nearby users communicate directly with each other, which leads to the proximity, hop, and reuse gains [5]. To improve these gains, most of the existing studies have chosen the reuse mode to the dedicated mode [6], where the reuse mode allows the D2D users to share the cellular user's spectrum and the dedicated mode assigns exclusive spectrum to the D2D users [7].

The D2D communications cannot be directly applied to vehicular communications due to the perfect channel state information (CSI) assumed available at the base stations (BS) or the D2D transmitters. This assumption does not hold in D2D Communication since the channel varies fast owning to the high mobility of vehicles and it is quite difficult, if not impossible, to estimate and feed the instantaneous CSI back to the transmitters. To this end, the D2D-enabled vehicular communications should carefully address the challenge caused by the channel uncertainty. The authors [8] proposed a spectrum and power allocation scheme to maximize the sum capacity of the V2I links with guarantee on the V2V links' signal-to-interference-plus-noise ratio (SINR) outage probability, but this in the case of delayed feedback of the CSI of the V2V links. Resource allocation and management in [9] have maximized the sum and minimum ergodic capacity of the V2I links while guaranteeing the SINR outage probabilities of the V2V links, based on only the large-scale channel information. A heuristic location dependent uplink resource allocation scheme has been proposed in [10] for D2D terminals, by spatial resource reuse with no requirement on full CSI, resulting less signaling overheads. Resource allocation schemes have been developed in [11] and [12] for the cases of permitting and not permitting spectrum sharing among the V2V links, by considering requirements on the reliability and transmission latency of the V2V links, respectively.

In this paper, both types of vehicular connections, i.e., V2I and V2V links, are proposed to support under the D2D-enabled cellular architecture. The V2I connectivity is enabled by macro cellular link and the V2V connectivity is supported through localized D2D link to achieve the twofold benefits of D2D-enabled cellular networks. High link capacity is preferred for V2I connections while safety-critical information of V2V connections places greater position on link reliability. Sum and minimum ergodic capacities (long-term average over fast fading) of V2I links are maximized with a minimum QoS guarantee for V2I and V2V links. While the V2V link reliability is ensured by maintaining the outage probability of received SINR below a small threshold. The proposed spectrum and power allocation is to maximize the sum ergodic capacity of the V2I links while guaranteeing the latency of the V2V links.

The rest of the paper is organized as follows. The system model is introduced in Section III. Section IV considers the sum V2I capacity maximization design with minimum QoS guarantee for V2I and V2V connections, whereas Section V addresses the resource allocation problem to maximize the minimum V2I capacity. Simulation results are presented in Section VI.

II. System Model

D2D-enabled vehicular communications network shown in Fig. 1, in which there exist N vehicles requires capable V2I communications, denoted as CUEs (cellular users), and L pairs of vehicles doing local V2V information exchange in the form of D2D communications, denoted as DUEs (D2D users). Assume that all communicating parties equipped with a single antenna. CUE set is denoted with N= 1,….., N and the DUE set is denoted with L = 1,….., L. To enhance spectrum efficiency, orthogonally assigned uplink spectrum of CUEs is reused by means of the DUEs considering uplink sources are much less intensively used and interfering at the BS is more manageable.

The channel power gain $h_{k,B}$, between CUE *k* and the BS is assumed to follow

$$h_{k,B} = g_{k,B}\beta_{k,B}AL_{k,B}^{-\gamma} \overset{\Delta}{=} g_{k,B}\alpha_{k,B}, \qquad (1)$$

Where $g_{k,B}$ is the small-scale fast fading power component and assumed to be exponentially distributed with unit mean, A is the path loss constant, $L_{k,B}$ is the distance between the kth CUE and the BS, γ is the decay exponent, and $\beta_{k,B}$ is a log-normal shadow fading random variable with a standard deviation ξ. Channel h_k between the mth D2D pair, interfering channel from the kth DUE to the BS, and interfering channel from the kth CUE to the mth DUE are similarly defined.

Assume that channel fading elements such as path loss and shadowing of all links, are known at the BS. Since they are usually dependent on user's location and vary on a slow scale [13,14]. Such information can be estimated at the BS for links between CUEs/DUEs and BS, i.e., α_{Bk} and $\alpha_{m,B}$ while for links between vehicles, i.e., α_m and $\alpha_{k,m}$.
The received SINRs on the BS for the kth CUE and at the mth DUE may be expressed as

$$\gamma_k^c = \frac{P_k^c h_{k,B}}{\sigma^2 + \sum_{m\in M} \rho_{k,m} P_m^d h_{m,B}} \qquad (2)$$

$$\gamma_m^d = \frac{P_m^d\, h_m}{\sigma^2 + \sum_{m\in M} \rho_{m,k} P_m^c h_{m,k}} \qquad (3)$$

Where P_k^c and P_m^d denote transmit powers of the kth CUE and the mth DUE, σ^2 is the noise strength, and $\rho_{k,m}$ is the spectrum allocation indicator, if $\rho_{k,m}$ = 1 it indicates the mth DUE reuses the spectrum of the kth CUE and $\rho_{k,m}$ = 0 in any other case . The ergodic capacity of the kth CUE is then given by

$$C_k = E[\log_2(1 + \gamma_k^c)] \qquad (4)$$

where the expectation E[•] is evaluated over the fast fading distribution.

III. CAPACITY MAXIMIZATION DESIGN FOR SUM CUE

In this section, to improve the vehicular communications performance a robust spectrum and power allocation scheme is developed. QoS variation for different types of links, i.e., huge capacity for V2I connections and more reliability for V2V connections is recognized. The sum ergodic capacity of N CUEs while guaranteeing the minimum reliability for each DUE is maximized. The reliability of DUEs is guaranteed through controlling the probability of outage events, where its received SINR γ_m^d is below a predetermined threshold γ_0^d . In vehicular networks, the radio resource allocation problem is formulated as

$$\max_{\substack{\{\rho_{K,M}\} \\ \{P_k^c\},\{P_m^d\}}} \sum_{k\in M} E[\log_2(1+\gamma_k^c)] \tag{5}$$

$$\text{s.t } E[\log_2(1+\gamma_k^c)] \geq r_0^c, \forall k \in N \tag{5a}$$

$$\Pr\{\gamma_m^d \leq \gamma_0^d\} \leq po,, \forall m \in L \tag{5b}$$

$$0 \leq P_k^c \leq P_{max}^c, \forall k \in N \tag{5c}$$

$$0 \leq P_k^d \leq P_{max}^d, \forall k \in L \tag{5d}$$

$$\sum_{m\in N} \rho_{m,k} \leq 1, \rho_{m,k} \in \{0,1\}, \forall m \in L \tag{5e}$$

$$\sum_{m\in N} \rho_{k,m} \leq 1, \rho_{k,m} \in \{0,1\}, \forall k \in L, \tag{5f}$$

Where γ_0^d is the minimum SINR needed by the DUEs to establish a reliable link is the minimum capacity requirement of the data rate intensive CUEs and Pr{•} evaluates the probability of the input and p0 is the acceptable outage probability at the physical layer of the V2V links. P_{max}^c and P_{max}^d are the maximum transmit powers of the CUE and DUE, respectively. Constraints (5a) and (5b) represent the minimum capacity and reliability requirements for each CUE and DUE, respectively. (5c) and (5d) guarantee that the transmit powers of CUEs and DUEs cannot go beyond their maximum limit. Spectrum of one CUE can only be shared with a single DUE and one DUE is only allowed to access the spectrum of a single CUE assured by (5e) and (5f). This assumption reduces the complexity.

A. Power Allocation strategies for Single CUE-DUE Pairs

In this, the optimal power allocation for each possible DUE and CUE reuse pair is studied. If the m[th] DUE sharing the band of the k[th] CUE is given, the power allocation problem for the single CUE-DUE pair is simplified into

$$\max_{P_k^c, P_m^d} E[\log_2(1+\gamma_k^c)] \tag{6}$$

$$\Pr\{\gamma_m^d \leq \gamma_0^d\} \leq p0 \tag{6a}$$

$$0 \leq P_k^c \leq P_{max}^c \tag{6b}$$

$$0 \leq P_m^d \leq P_{max}^d \tag{6c}$$

According to the Lemma 1, the optimal power allocation solution to optimization problem (6) is given by

$$P_k^{c^*} = \min\left(P_{max}^c, P_{d,max}^c\right) \tag{7}$$

And

$$P_m^{d^*} = \min\left(P_{max}^d, P_{c,max}^d\right) \tag{8}$$

Eq (7) & Eq (8) gives the optimal power allocation for a single CUE-DUE pair.

B. Pair Matching for All Vehicles

In the next step, if the minimum QoS requirement for the CUE, i.e., (5a), is not satisfied then there is a need to eliminate those CUE-DUE combinations even when the optimal allocation scheme obtained from (7&8) is applied.

The closed-form expression for the ergodic capacity of the k[th] CUE when sharing spectrum with the mth DUE, described as

$$C_{m,k}(P_m^c, P_k^d) \triangleq E[\log_2(1+\gamma_m^c)] \tag{9}$$

Substituting the optimal line power allocation (7&8) in (9) yields the most ergodic capacity performed while the k[th] CUE shares its spectrum with the m[th] DUE, denoted as $C_{k,m}^*$. If it is less than r_0^c , then this combination cannot meet the minimal capability requirement for the CUE. Therefore, the sort of CUE-DUE pair isn't always feasible and set $C_{k,m}^* = -\infty$, i.e.

$$C_{k,m}^* = \begin{cases} C_{k,m}(P_k^{c^*}, P_m^{d^*}), & if C_{k,m}(P_k^{c^*}, P_m^{d^*}) \geq r_0^c \\ -\infty, & otherwise. \end{cases} \tag{10}$$

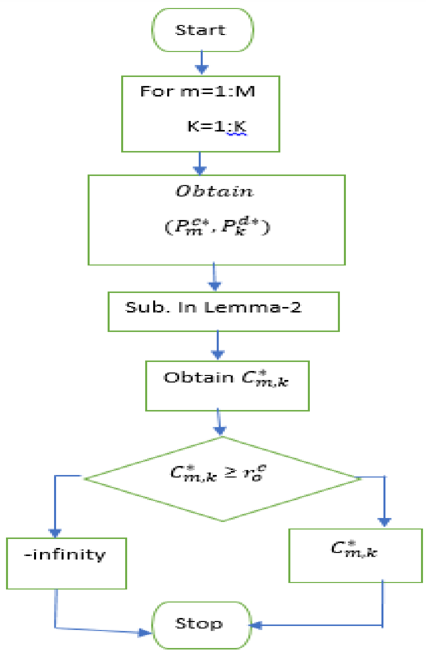

Fig.2.Flow chart of Optimal Resource Allocation Algorithm-I for (5) in D2D-Enabled Vehicular Communications

After evaluating all possible combinations of the CUE-DUE pairs, the resource allocation problem (5) reduces to

$$\max_{\{\rho_{m,k}\}} \sum_{m\in M} \sum_{k\in K} \rho_{m,k} C_{m,k}^* \tag{11}$$

$$\sum_{m\in M} \rho_{m,k} \leq 1, \rho_{m,k} \in \{0,1\}, \forall k \in K \tag{11a}$$

$$\sum_{k\in K}\rho_{m,k}\leq 1,\rho_{m,k}\in\{0,1\},\forall m\in M \tag{11b}$$

which seems to be a most weight two-part matching problem and may be effectively resolved by means of the Hungarian approach in polynomial time [15].Optimal solution to the resource allocation problem in (5) using Algorithm-I for D2Denabledvehicular communications can be summarized inFigure.2. Suppose an accuracy of ε is required, the bisection search for the optimal power allocation of a single CUE-DUE pair as given in (8&9) requires log(1/ε) iterations. This leads to the total complexity of O(MK log(1/ε)) to compute the optimal power allocation for all CUE-DUE pairs. The Hungarian method will resolve the pair matching problem in O(K^3)time with the assumption K.≤M Therefore, the proposed algorithm total complexity is given by O(MK log(1/ε) +K^3).

IV. Minimum CUE Capacity Maximization Design

The design of sum capacity maximization considered in Section III can assure a high throughput from the network operator's perception. But especially for those vehicles experiencing bad channel conditions, it tends to be unfair from each CUE's point of view. In such a case, the CUEs with bad channel conditions will be sacrificed in exchange for the overall performance improvement. In this section, address this issue by maximizing the minimum capacity among all CUEs so as to provide a more uniform performance across all CUEs. The proposed optimization problem is stated as

$$\max_{\substack{(\rho_{k,m})\\ \{P_k^c\},\{P_m^d\}}}\ \min_{k\in M} E\left[\log_2(1+\gamma_k^c)\right] \tag{12}$$

s.t. (5a) – (5f)

A. Design of Power allocation

The proposed resource allocation problem in (13) can be solved, by using optimal power control results given in (7&8) for each CUE-DUE pair and the original problem in (12) is simplified into the following form

$$\max_{\{\rho_{k,m}\}}\ \min_{k\in M}\sum \rho_{k,m}\ C_{k,m}^{*} \tag{13}$$

$$\sum_{k\in M}\rho_{k,m}\leq 1,\quad \rho_{k,m}\in\{0,1\},\vartheta m\varepsilon M \tag{13a}$$

$$\sum\nolimits_{m\in M}\rho_{k,m}\ \leq 1,\ \ \rho_{k,m}\in\{0,1\},\vartheta k\varepsilon L \tag{13b}$$

Here, further attempt to develop a low-complexity algorithm to solve the optimization problem in (13) through the Hungarian method which is computationally complex. Optimal solution to the resource allocation problem using Algorithm-II for D2Denabledvehicular communications can be summarized in Figure.3. and it comprises with two essential parts.

- Initialize an every one of the zero grid F of size K × M.

$$F_{k,m}=\begin{cases}1, & if\ C_{k,m}^{*}<\\ 0, & otherwise\end{cases} \tag{14}$$

- Scan every component of the limit network capacity, $\{C_{k,m}^{*}\}$, got from Algorithm 1 and in the event that it is not exactly set the comparing section of F to 1 and leave it as generally, i.e., $\forall_{m,k}$.
- Hungarian method is applied to F and return the lowest total cost i.e., the sum of all the assigned elements which is denoted as c.

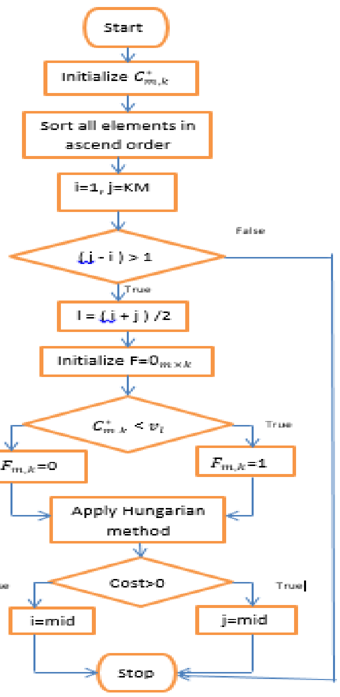

Fig.3. Flow chart of Optimal Resource Allocation Algorthm-II for (12) in D2D-Enabled Vehicular Communications

Next deals with the ordering all KM elements of optimal matrix$C_{k,m}^{*}$, and then searches for the position of the optimal minimum ergodic capacity using bisection search method. At last, Hungarian method yields the spectrum when the bisection search ends.

The complexity of the proposed algorithm lies in the generation of the capacity matrix $C_{k,m}^{*}$,whose complexity is O(MK log(1/ε)), the ordering of all elements in whose computational complexity is O(MK log(MK)), and the bisection search for the optimal value based on the Hungarian method with complexity of O (K^3 log K) if K≥M. Then the total computational complexity of Method-II amounts to O (MK log(1/ ε) + MK log(MK) +K3logK)

V. Results

The simulation parameters for the highway and urban cases are considered from the 3GPP TR 36.885 [1]. According to Spatial Poisson process, the vehicles are dropped on the roads and the vehicle density is determined by the vehicle speed. The parameters considered to simulate a system in Table 5.1 (a) are same for both urban and highways and the Table 5.1 (b) shows urban and highways are differentiated with vehicle speed, lane width and number of lanes.

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Table 5.1 Simulation parameters [1], [16]
(a)

Parameter	Value
Bandwidth	10 MHz
Cell radius	500 m
BS antenna height	25 m
BS antenna gain	8 dBi
BS receiver noise figure	5 dB
Distance between highway and BS	35 m
Vehicle antenna height	1.5 m
Vehicle antenna gain	3 dBi
Vehicle density	Average inter vehicle distance is 2.5 sec * absolute vehicle speed
Carrier frequency	2 GHz
Minimum capacity of DUE r_0^c	0.5 bps/Hz
SINR threshold for DUE γ_0^d	5 dB
Reliability for DUE p_0	0.001
Number of DUE's, *L*	20
Number of CUE's, *N*	20
Maximum CUE transmit power P_{max}^c	17, 23 dBm
Maximum DUE transmit powerP_{max}^d	17, 23 dBm
Vehicle drop model	Spatial Poisson Process
Noise power σ^2	-114 dBm
Vehicle receiver noise figure	9 dB
Bisection search accuracy ϵ	10^{-5}

Table 5.1 Simulation parameters [1], [16]
(b)

Parameter	Freeway case channel	Urban case channel
Absolute vehicle speed *v*	70 km/h	15 km/h
Lane width	4 m	3.5 m
Number of lanes	3 in each direction (6 in total)	2 in each direction (4 in total)

Table 5.2 describes the channel models for V2I and V2V links in freeway and urban cases. The channel models for V2I link is same for both urban and highways as shown in Table 5.2 (a) and for V2V link is shown in Table 5.2(b).

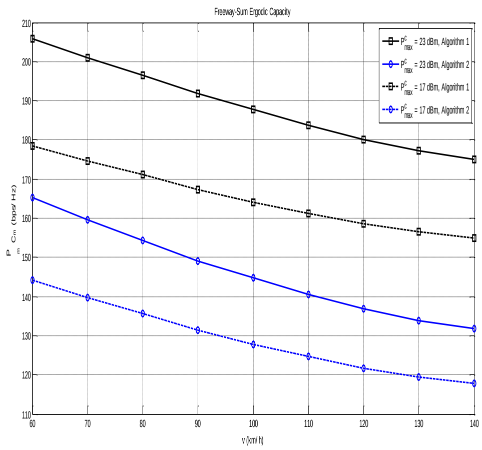
Table 5.2
(a) Channel Models For V2I Link [2]

Parameters	mathematical model
Pathloss model	128.1 + 37.6log10 d, d in km
Shadowing distribution	Log-normal
Shadowing standard deviation	8 dB
Decorrelation distance	50 m
Fast fading	Rayleigh fading

Table 5.2
(b) Channel Models For V2V Link [2]

Parameters	Freeway case channel	Urban case channel
Pathloss method	LOS in WINNER + B1	WINNER + B1
Shadowing distribution	Log-normal	Log-normal
Shadowing standard deviation	3 dB	3 dB for LOS &4 dB for NLOS
Decorrelation distance	25 m	10 m
Fast fading	Rayleigh fading	Rayleigh fading

Fig.4. and Fig.5.. shows the sum and minimum ergodic capacities of all CUEs evaluated by increasing vehicle speed on highways and urban areas. From the Fig.2. and Fig.3., as the vehicles move faster, both the sum and minimum CUE capacities decreases, because higher speed induces sparser traffic. This would effect on average increase inter-vehicle distance and give rise to less reliable V2V links with lower received power. As such, less interference from CUEs can be tolerated.



(a)Freeway Sum Ergodic Capacity

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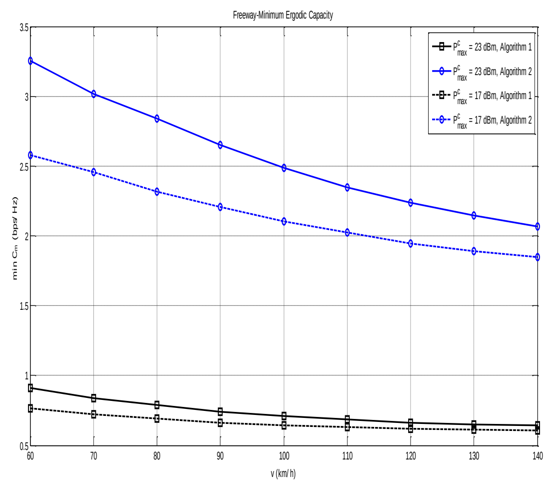
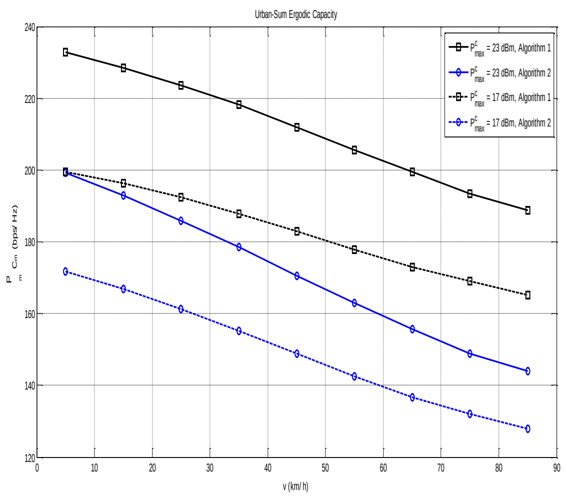
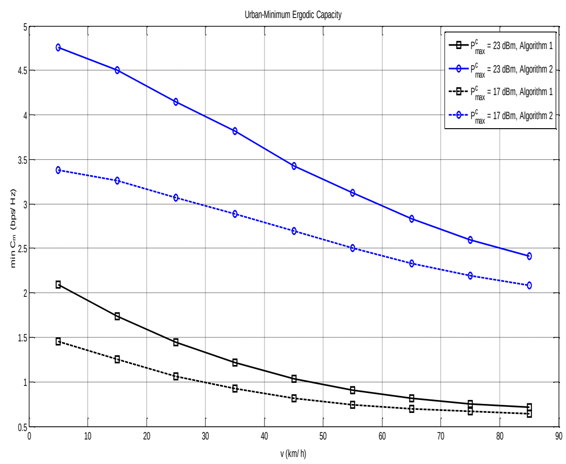


(b)Freeway Minium Ergodic Capacity

Fig. 4. Capacity performance of CUEs with the varying vehicle speed ϑ on the highways.



(a)Urban Sum Ergodic Capacity



(b)Urban Minimum Ergodic Capacity

Fig.5. Capacity performance of CUEs with the varying vehicle speed ϑ in urban areas.

It shows that Algorithm 1 achieves higher sum ergodic capacity than Algorithm 2 and the Algorithm 2 achieves higher minimum ergodic capacity than Algorithm 1. This makes sense since Algorithm 1 takes to maximize the sum ergodic capacity while Algorithm 2 aims to maximize the minimum ergodic capacity as its design objective. It also reveals from the Fig.4. and Fig.5. that the capacity performance is high in urban cases than on highways.

VI. Conclusion

In this work, the spectrum sharing and power allotment structure are explored for D2D-empowered vehicular systems using two algorithms. Because of High mobility and fast channel variations, the instantaneous CSI is difficult to follow in vehicular communication. In the case of traditional resource allocation schemes for D2D-based cellular networks requires full CSI. To address this issue, QoS necessities of vehicular communications considered and differentiated. Thus, formulated optimization issues aiming to design a resource allocation scheme based on slowly varying large-scale fading information. Powerful algorithms have been implemented to maximize the sum and minimum ergodic capacity of V2I links, while ensuring reliability for all V2V links in urban areas and highways.

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