Transmission Capacity Analysis of Vehicular Relay Assisted Device-to-Device Communication

***Priyanka Singh*[1] *and Rajoo Pandey*[2]**
Department of Electronics & Communication Engineering
National Institute of Technology, Kurukshetra, India
***E-mail**:- priyanka_31805108@nitkkr.ac.in[1], rajoo_pandey@nitkkr.ac.in[2]*

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Abstract

The transmission capacity of vehicular relay assisted networks coexisting with cellular networks is studied in this paper. The transmission capacity was analysed in both underlay and overlay cases. Vehicle-to-Vehicle networks, cellular users and relay nodes (RNs) are all modelled using poison point process based on stochastic geometry. Then the probability of RN existence and the relay link distance expectation for obtaining the successful transmission probabilities for V2V is calculated. Further, the transmission capacity of V2V communication with relay nodes in both underlay and overlay modes were obtained. Finally, simulation results show that V2V transmission capacity is improved by using relay transmission and influenced by various factors like V2V density, cellular user density, power, V2V link distance, but also the way of using RNs in V2V communications.

***Keywords:** - Vehicle-to-Vehicle communications, D2D communication, Relay transmission, Overlay, Underlay, Transmission capacity.*

INTRODUCTION

As the number of vehicles is increased by 40%, spectrum shortage is becoming a serious problem in Vehicle-to-Vehicle communication. V2V communication allows vehicles to communicate and exchange information directly [1]. Transmission Capacity is an important challenge in Vehicle-to-Vehicle communication. The fifth-generation technologies (5G) have lots of new promising technologies like MIMO, Device-to-Device communication, NOMA etc., for transmission. One of these technologies is D2D communication which allows transmission with a direct link between two devices [2]. The advantages of D2D communication are reduced transmission power, improved transmission capacity and spectrum. D2D communication also affects the system with harmful interference because it reuses the frequency spectrum. It may decrease the overall performance of the network. Transmission capacity for D2D communication has been analysed previously in some literature. But still, the main goal was to further improve the transmission capacity of the network. An interference area limited scheme was proposed to reduce the interference and enhance the capacity in D2D communication and cellular networks [3]. After that, an optimization technique was proposed to enhance the capacity of the system by further studying the resource and power allocation between Device-to-Device users and cellular users. In this technique, data was transmitted in a bidirectional way, hence improves the capacity [4]. After that, an optimal technique was introduced in [5] where D2D communication was assisted by cellular users in the network.

Furthermore, to enhance the capacity and spectrum efficiency, relay technology [6] has been proposed in Device-to-Device communication. The advantages of this technology are it can improve connectivity due to its diverse nature. It also provides a way to improve the coverage area. It analysed the outage probability and transmission capacity in D2D communication. Hassan et al. [7] further analysed the multi-relay network and proposed a resource allocation technique. In this spectrum sharing system, the outage probability with interference and the outage probability of cognitive Amplify-and-Forward were analysed. An inter-cluster Device-to-Device retransmission scheme was proposed in [8] where the Device-to-Device network was able to choose the no. of collective relays as per their requirement. That relay link can enhance the transmission capacity by using the corresponding spectrum of the cellular network in a coexisting network with no relay link transmission.

In [9], the scenario that D2D communication and cellular networks can coexist is considered. They can perform transmission using potential relay nodes [10-11]. Mobile terminals were used as potential relay nodes. In [12], these two modes were analysed in details. 1) Overlay mode: D2D users and cellular users do not share spectrum resources in this mode. Thus, there is no interference between them. 2) Underlay mode: D2D users share the spectrum resources with cellular users. There exists interference between them.

In [13], Device-to-Device transmission capacity was analysed in overlay mode. The effect of cellular user density, Device-to-Device link distance and power on transmission capacity were also analysed. In [14], they further analysed the relay technology in vehicular communication. In this study, two types of vehicles were considered. Service Vehicles (SVs) which requires the services and Helper vehicles (HVs) which assists the service vehicle and provides the data service and helps in transmission. Any vehicle can act as a Service Vehicles (SVs) or Helper Vehicle (HVs). In this transmission, capacity was analysed in overlay mode.

After that, in [15], transmission capacity for relay assisted vehicular communication was analysed. In this model, two types of vehicles were used. Principle vehicle (PV), which requests the spectrum from Vehicle-to-Vehicle communication and Assistant Vehicle (AV) which works as a relay and assist the principle vehicle and provides transmission between two principle vehicles.

In this paper, a model has been considered where Vehicle-to-Vehicle communication coexists with the cellular users. Vehicular communication allows the vehicle to communicate with each other directly. In this scenario, two kinds of vehicles were considered. Principle Vehicles (PVs) and Assistant Vehicles (AVs). They work in overlay and underlay mode. In overlay mode, Vehicle-to-Vehicle communication and cellular communication both are allocated different spectrums for data transmission. So, there is no interference between them. In underlay mode, Vehicle-to-Vehicle communication and cellular users share the same spectrum resources. There exists interference between Vehicle-to-Vehicle communication and cellular users. In this study, both modes were considered.

First, Principle vehicles (PVs), Assistant vehicle (AVs) and networks were modelled by using Poisson Point Process (PPP). Then for each case, the relay transmission was analysed in two parts the successful transmission capacity and the expectation of relay link distance. With the different mechanism, transmission capacities were obtained in both overlay and underlay mode. The results verify that the Vehicle-to-Vehicle transmission capacity was influenced by various factors like user density in the networks, variable V2V link distance and the process of using the AVs as a relay in V2V transmission.

The general form of successful transmission probabilities was derived in Section IV and V, and Vehicle-to-Vehicle transmission capacity was analysed in overlay and underlay mode. Section VI presents the numerical results. Finally, In Section VII, conclusions were presented.

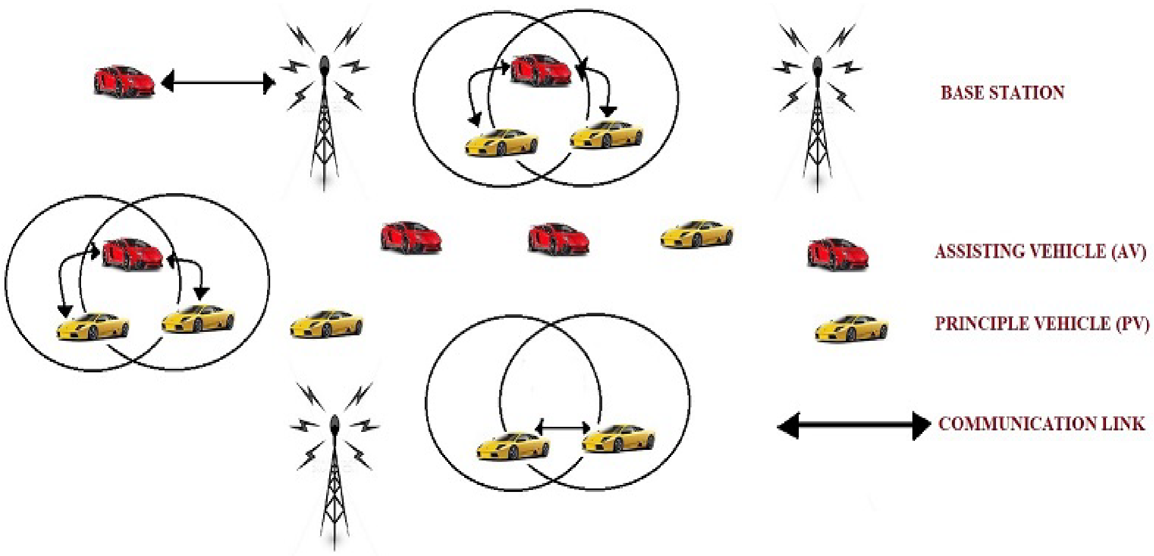

Fig. 1: Scenario of vehicular relay-assisted D2D communication

SCENARIO DESCRIPTION AND SYSTEM MODEL

First, the basic scenario of the network is explained then the system model is described. The model contains cellular networks, vehicular networks, wireless link etc.

A. Scenario Description

Cellular users use the cellular frequency spectrum for transmission, as shown in Fig. 1. Principle vehicles (PVs) and Assistant vehicles (AVs) reuses the uplink resources for transmission. All the vehicles have one omnidirectional antenna radio, and the network uses time division duplex (TDD) mode. At the physical layer, by using orthogonal frequency-division multiplexing (OFDM) uplink frequency spectrum is divided into K (K= M + N) frequency-flat subchannels. Cellular vehicles and principle vehicles both use the full set of sub-channels.

B. Network Models

Vehicular networks are presented using a two-dimensional plane by using the theory of stochastic geometry; these assumptions are presented. All these networks are modelled by using a stationary PPP on a two-dimensional plane $\mathfrak{R}$.

Assumption 1: A stationary PPP on the two-dimensional plane $\mathfrak{R}$ is formed by cellular users. Cellular user density is indicated as λ_0. The transmission power in the cellular network is denoted as P_0.

Assumption 2: The transmitter of principle vehicles forms a PPP with principle vehicles (PVs) density λ_1. The transmission power of the principle vehicle is indicated as P_1.

Assumption 3: The assisting vehicles (AVs) forms a PPP with AVs density λ_2. The transmission power of assisting vehicle is denoted as P_2. Source principle vehicle uses assisting vehicles in forwarding the message to the destination principle vehicle. Principle vehicle can select assisting vehicle randomly from multi assisting vehicles if existed and uses assisting vehicle in relaying messages.

Assumption 4: A typical receiver of system S_j, j Є {0, 1, 2} is assumed to be located in origin according to the palm theory [11]. Statistics of PPP does not influence by it.

C. Channel Models

A Rayleigh fading channel is assumed for the wireless vehicular networks. The model for a wireless channel can be shown as

$$P_{r\,x} = \delta\, P_{t\,x}\, |D|^{-\alpha} \qquad (1)$$

Transmitter power is represented by $P_{t\ x}$, and receiver power is represented by $P_{r\ x.}$ δ indicates Rayleigh fading coefficient. α indicates the path loss exponent. The distance between transmitter and receiver is represented by |D|.

Principle vehicle and assisting vehicle reuse the resources of cellular users. The receiver suffers from the interferences produced by Vehicle-to-Vehicle communication link, cellular users, and other links.

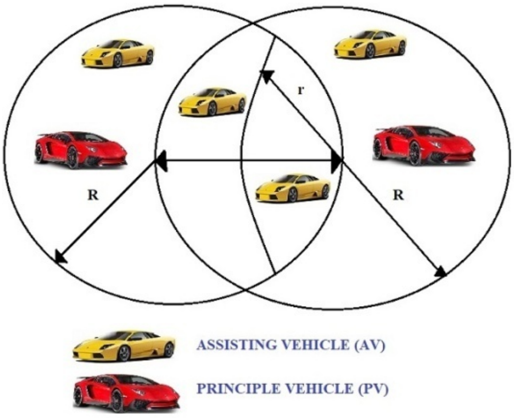

Fig. 2: Network model for vehicular D2D communication

SYSTEM MODEL

First, the assisting vehicle probability and expectation of assisting vehicle link distance between two communication principle vehicle and assisting vehicle are obtained. Then, the successful transmission probability of the receiver is deduced.

A. Existence probability and expectation of assisting vehicles (AVs) distance

The distance between source principle vehicle and destination principle vehicle is represented by D. Based on assumption 3, the principle vehicle uses assisting vehicle in forwarding the message when assisting vehicles are detected in the shaded region of Fig. 2. To calculate the area of the shaded region equation 1 is used,

$$S = (2\pi/3-\sqrt{3}/2)\, R^2 \qquad (2)$$

From assumption 3, the density of assisting vehicle is λ_2. So, the existence probability Pr_e of assisting vehicle (AV) in the shaded region is stated by

$$Pr_e = 1 - e^{-\lambda_2 S} \qquad (3)$$

The average link distance between principle vehicle (PV) and assisting vehicle (AV) can be calculated by using the method of mathematical expectation.

B. Probability of successful transmission for communication link

Noise and interference from principal vehicle to assisting vehicle, interference from cellular users affects the transmission link. All interferences were considered for computing the general form of successful transmission. Packet's transmission becomes a serious problem which is caused by vehicular traffic noise in practical vehicular networks. As we know that principle vehicles (PVs) and assisting vehicles (AVs) share the spectrum resources with other users. At the typical receiver, the signal-to-interference ratio (SIR) of system S_n, is (n is 0, 1, 2) is defined by

$$SIR_n = \frac{P_n \delta_{no} R_{no}^{-\alpha}}{\Sigma_{j \epsilon \{0,1,2\}} I_j} \quad (4)$$

The interference power is denoted by $I_j = (P_j / P_n) \Sigma_{k \in \Pi j}$, and δ_{n0}shows Rayleigh fading coefficient and the link distance from the transmitter to receiver is denoted by R_{n0}.

TRANSMISSION CAPACITY ANALYSIS IN THE OVERLAY MODE

Principle vehicle (PV) and assisting vehicle (AV) work in overlay mode. To analyse the performance of the network, the influence of different PV to PV links and PV to AV links is considered.

A. PV to PV transmission capacity assisted by AVs

Two cases were considered for forwarding the messages through assisting vehicles (AVs).

Case 1: Principle vehicle (PV) starts the transmission only if assisting vehicle (AV) exist in shaded part as shown in Fig. 2.

Case 2: If there exists an assisting vehicle (AV) in the shaded part, then the pair of source PV and destination PV utilizes this AV for forwarding signals; else, it transmits the signal by a direct communication link.

The detailed analysis of both cases is being studied in sections below this:

Case 1: Transmission distance extension

The PV is not able to forward signals if no AV is available for transmission in this case. Since AV relay transmission uses TDD mode, PV to PV transmission time is the same as that of AV transmission time. PV must use AV to transmit the message in this scenario. The density of activated PVs or AV is (1/2) $\lambda_1 Pr_e$. The transmission capacity is calculated by the multiplication + of successful transmission probability and the user density. PV to AV and AV to PV successful transmission probabilities in overlay mode of case 1 can be explained as

$$\Pr(SIR_{PV2AV,\,ov1} \geq T_2) = e^{-\frac{1}{2}\lambda_1 Pr_e C_\alpha T_2^{\frac{2}{\alpha}} A^2 R^2 \left[\left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}} + 1\right]} \quad (5)$$

$$\Pr(SIR_{AV2PV,\,ov1} \geq T_2) = e^{-\frac{1}{2}\lambda_1 Pr_e C_\alpha T_2^{\frac{2}{\alpha}} A^2 R^2 \left[\left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}} + 1\right]} \quad (6)$$

In case 1, the transmission capacity of PV to PV communication in overlay mode can be written as

$$C_{AV,\,ov1} = \frac{1}{2}\lambda_1 Pr_e \times \Pr(SIR_{PV2AV,\,ov1} \geq T_2) \times \Pr(SIR_{AV2PV,\,ov1} \geq T_2) \quad (7)$$

Case 2: Transmission Capacity Improvement

Source PV forwards the message to destination PV via a direct link if there exists no AV in the shaded part in this case. The density of AVs with direct transmission link is $(1 - Pr_e)\lambda_1$. The densities of transmission from source principle vehicle (PV) to selected assisting vehicle (AV) and selected assisting vehicle (AV) to destination principle vehicle (PV) are both $\frac{1}{2}\lambda_1 Pr_e$. In case 2, the PV to PV communication transmission capacity in the overlay mode is given by

$$\Pr(SIR_{PV2PV,\,ov2} \geq T_1) = e^{-\lambda_1 C_\alpha T_1^{\frac{2}{\alpha}} R^2 \left[1 - \frac{1}{2}\Pr + \frac{1}{2}\Pr\left(\frac{P_1}{P_2}\right)^{\frac{2}{\alpha}}\right]} \quad (8)$$

B. Transmission capacity gain

To analyze the transmission capacity gain in the network from assisting vehicles (AVs) in overlay mode, PV to PV transmission capacity without AV is calculated.

$$C_{AV,\,ov2} = \lambda_1 (1 - Pr_e) \times \Pr(SIR_{PV2PV,\,ov2} \geq T_1) + \frac{1}{2}\lambda_1 Pr_e \times \Pr(SIR_{AV2PV,\,ov1} \geq T_2) \Pr(SIR_{PV2AV,\,ov1} \geq T_2) \quad (9)$$

C. PV to PV transmission capacity with variable communication link distance

PV to PV link distance is a random variable in a practical vehicular D2D relay system. But in the above analysis, we have studied that the link distance between PV to PV is a fixed value, D=R. To fill the space between practical and theoretical model, the AV transmission capacity is analysed with variable AV to AV link distance in overlay mode. because PVs and AVs both share resources; the influence of AV is always studied. AV density is supposed to be big enough, i.e., the condition that $Pr_e = 1$, so that AV always exists and assist in the transmission of PV to PV communication. The minimum and maximum transmission distance between the source PV transmitter and destination PV transmitter is defined as R_{max} and R_{min}. The distance R = D obeys uniform distribution in $[R_{min}, R_{max}]$, $(0 \leqq R_{min} < R_{max})$.

TRANSMISSION CAPACITY ANALYSIS IN THE UNDERLAY MODE

The performance of PV to PV communication with AVs is analysed in the underlay mode in this section. PV to PV communication and AVs shares the spectrum resources with cellular users. So, the effect of the cellular system is also taken into consideration in this section.

A. PV to PV transmission capacity assisted by AVs

Case 1: Transmission distance extension

In underlay mode, the probabilities of successful transmission from PV to AV and from AV to PV of case 1 can be written as

$$C_{AV,\,un1} = \frac{1}{2}\lambda_1 Pr_e \times Pr\,(SIR_{PV2AV,\,un1} \geqq T_{2)} \times Pr\,(SIR_{AV2PV,\,un1} \geqq T_{2)} \qquad (10)$$

Case 2: Transmission Capacity Improvement

When there exists no AV in the shaded part, then PV to PV communication should use a direct link to forward signals.

$$C_{AV,\,un2} = \lambda_1\,(1 - Pr_e) \times Pr\,(SIR_{PV2PV,\,un2} \geqq T_{1)} + \frac{1}{2}\lambda_1 Pr_e \times Pr\,(SIR_{AV2PV,\,un2} \geqq T_2)\,Pr\,(SIR_{PV2AV,\,un1} \geqq T_2) \qquad (11)$$

B. Transmission capacity gain

The interference in the underlay mode is more complex than the overlay mode. To analyze the transmission capacity gain in the network from assisting vehicles (AVs) in underlay mode, the first PV to PV transmission capacity without AV is calculated.

C. PV to PV transmission capacity with variable communication link distance

The AV transmission capacity with variable PV to PV link distance in the underlay mode is obtained in this section. The density of AVs is assumed to be large enough, i.e., the condition that $Pr_e = 1$, so that PV to PV transmission can be assisted by AV always similar to overlay mode. The distance R = D obeys uniform distribution in $[R_{min}, R_{max}]$, $(0 \leqq R_{min} < R_{max})$.

SIMULATION RESULTS AND DISCUSSION

In this section, the PV to PV transmission capacity results are evaluated. The key parameters of the network are given in Table I. the simulation results have been analysed using MATLAB.

Table I: Simulation parameters

Parameter	Value
Cellular user density (λ_0)	0.0001 m^{-2}
PV density (λ_1)	0.0003 m^{-2}
AV density (λ_2)	0.0002 m^{-2}
Cellular power (P_0)	24 dBm
PV transmission power (P_1)	17.9 dBm
AV transmission power (P_2)	17.9 dBm
Link distance (D)	33 m

The connection of PV to PV transmission capacity and AV density with respect to variable PV to PV link distance in overlay mode is shown in Fig. 3. The results show that the capacity of case 2 is higher than the case with AVs because PV to PV communication uses a direct link for transmission. The PV to PV transmission capacities of case 2 and case 1 are equal under higher λ_2 since PV can always find AVs for transmission.

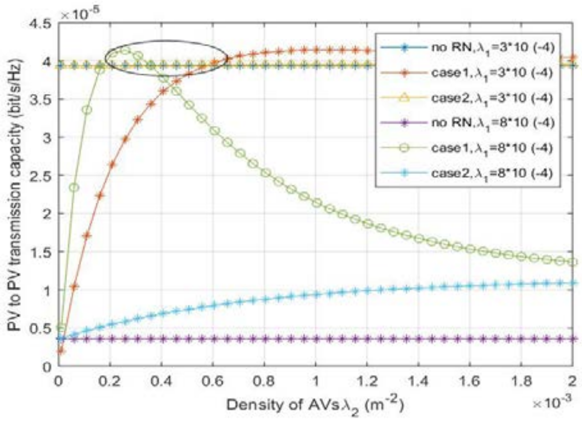

Fig. 3: PV to PV transmission capacity vs. potential density of AVs under different PV to PV density in overlay mode

It also shows that the curves of transmission capacity in case 1 increases at first and then decreases. This is because the gain from AVs is dominated at first, then gain is pull down by the harmful noise and interference from AV relay transmission as AV density increases. The ellipse shows that PV to PV transmission capacities can have the same value under different PV density in case 1. This is due to the fact that the number of AVs which assist PVs can be equal under the same direct PV to PV link distance.

Fig. 4 shows the transmission capacities of case 1 and case 2 in underlay mode. PV to PV transmission capacities of case 2 is always greater than case 1 because PVs can always forward the message using a direct link. But in the case of higher AVs density, the capacities of case 1 and case 2 can be equal.

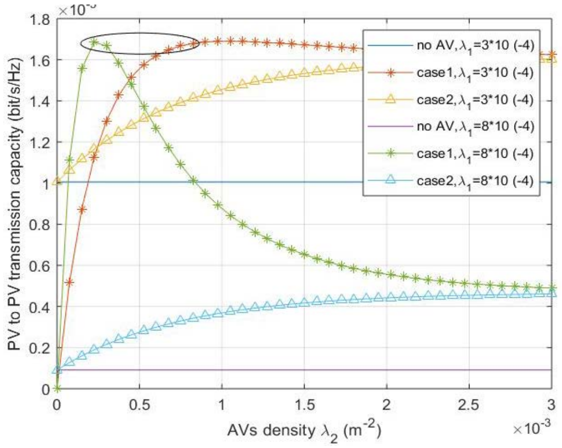

Fig. 4: PV to PV transmission capacity vs. potential density of AVs under different PV to PV density in underlay mode

In the case of underlay mode, the transmission capacities curve rises at first due to the gains from AVs and then as the interference and noise increase, the curve declines. The interference and noise are more in the case of underlay mode because PV and AV both shares spectrum resources. The ellipse shows that transmission capacities of PV to PV communication can be equal under higher densities of AV. In Fig. 4 it shows the transmission capacities of PV to PV transmission with different AV density under different PV to PV density.

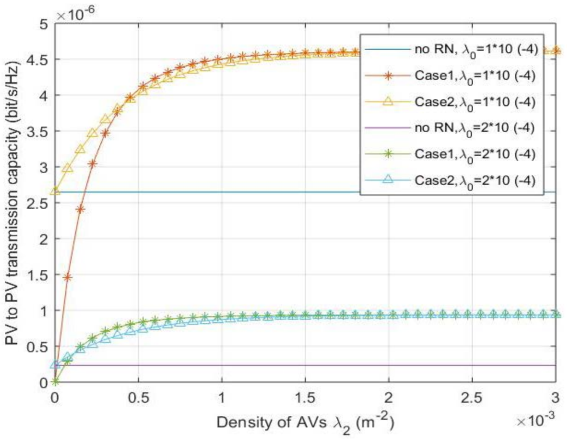

Fig. 5: PV to PV transmission capacity vs. potential density of AVs under different cellular user density in underlay mode

Fig. 5 shows the PV to PV transmission capacity with different AV density under different cellular user density. It shows the influence of shared spectrum resources on AV transmission. We can see that the interference becomes more serious as the cellular density increases, which leads to a lower PV to PV transmission capacity. PV to PV transmission in case 1 suffers more from the interference of cellular communication because it only depends upon AV transmission. In case 2, the influence is smaller because there exists a PV to PV direct link for transmission. Fig. 5 also shows that when λ2 is small, the PV to PV transmission capacity of case 1 is also low.

CONCLUSION

The transmission capacities of PV to PV transmission with the assistance of AVs are analysed in overlay and underlay mode in vehicular D2D relay system in this paper. By using stochastic geometry, PVs and AVs are modelled in PPP. The close-form expression for transmission distance extension and promotion of PV to PV transmission capacity with AVs is derived. The equation of transmission capacity gains is also derived. Then the influence of variable PV density, cellular user density on PV to PV transmission capacity has been analysed, which is useful in the case of practical system design. The advantage of AV transmission to PV to PV communication is verified from the simulation results. The way of using the AVs also affects the transmission capacity of the system. The results also show that the PV to PV transmission capacity is also affected by PV to PV direct link distance, cellular user density, PV and AV density which introduce interference and noise to the vehicular D2D communication.

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