Joint Power control and Resource sharing for 5G-V2X communication in Cellular Networks

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***Abstract*—Vehicle to Everything (V2X) communication in 5G cellular networks plays a pivotal role in enhancing road safety, traffic efficiency and cooperative driving. A novel joint spectrum and power allocation scheme is implemented based on large-scale fading channel information in order to maximise the throughput of V2V users while maintaining the quality of service (QoS) of V2I users. In our system model, V2V users reuse the spectrum of V2I users in order to enhance the spectrum efficiency. An optimization technique namely weighted bipartite matching is used for spectrum reuse pair selection which is solved by using the Hungarian method. The throughput of V2V and V2I users is measured by varying the number of vehicles for a fixed number of V2I and V2V users respectively. The relationship between the throughput of V2V and V2I with SINR for different values of pathloss exponent is also discussed. The CDF of the proposed method is also compared with the existing scheme in terms of outage probability which proves the superiority of our work. Additionally, the computer simulations confirm the effectiveness of our work.**

***Index Terms*—V2X communication, V2V, V2I, Spectrum reuse, Power control, 5G.**

I. Introduction

The fifth generation (5G) intelligent transportation systems (ITSs) are expected to experience a revolution with reference to road safety, enhanced travel services, and efficient transportation as a result of recent advancements in autonomous driving technologies and electric engines [1]. While the development of completely autonomous vehicles is still ongoing, there is a need for further enhancement in areas such as autonomous platooning, accident warning and prevention and inter-vehicle cooperation [2]. The advent of vehicular-to-everything (V2X) in 5G networks aims to improve driving efficiency, safety, and sustainability. V2X paves the path for autonomous driving by delivering reliable and quick services [3]. As a result, V2X communication has been recognized as a crucial element in the development of future wireless networks, gaining significant attention from both industrial and academic circles [4]. V2X communication is developed with the objective of facilitating the exchange of information which, includes Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), Vehicle to Pedestrian (V2P), and Vehicle to Network (V2N) communication. V2V communication enables the sharing of information exclusively between nearby vehicles, while V2I communication utilizes roadside infrastructure to grant vehicles internet access, allowing for the dissemination of information over larger geographical areas [5].

There are various standards used for vehicular communication such as Dedicated short-range communication (DSRC) coined by IEEE and V2X communication in 5G cellular networks coined by 3^{rd} generation partnership project (3GPP) [6]. V2X is a wireless communication protocol designed for connected vehicles and ITS. It is a technology that allows vehicles to communicate with one another, roadway structures, and other connected devices, such as smartphones and smart traffic lights [7]-[8].

Vehicular communication enabled by V2X technology offers several benefits such as reduced latency, large network capacity and enhanced quality of service (QoS). V2V communication causes interference with the cellular network if the spectrum is not distributed appropriately [9]. There are two modes of communication in terms of spectrum sharing, namely the underlay mode and the overlay mode [10]. In the underlay mode, vehicular users (VUs) and cellular users (CUs) use the same spectrum at the same time. However, in the overlay mode, the frequency band is divided into two halves, one for CUs and the other for VUs.

This paper focuses on the underlay mode of communication. Since VUs and CUs use the same spectrum at the same time, hence VUs cause co-channel interference with the CUs. Therefore, it is particularly important to minimize mutual interference and reduce energy consumption by controlling the transmit power of VUs and CUs. Further, the impact of interference on CUs can be reduced by controlling the power of VUs. Hence, power control is important for maximizing the performance of vehicular communication networks. An extensive literature review indicates solving power control [11] or spectrum allocation [12]-[13] issues in V2X communication. However, these approaches neglect the simultaneous impact of power control and spectrum allocation on the network performance. Therefore, researchers have started to consider joint power control and spectrum allocation to improve network performance in V2X communication.

A. Related Work

The issue of allocating resources in wireless communication systems has received considerable interest and has been thoroughly examined in recent research studies. In [14], the authors investigate resource management strategies for V2X systems considering imperfect Channel State Information (CSI) and also formulate a problem within an optimistic scenario, assuming that the distribution of uncertain CSI is deterministic and can be precisely known at the evolved NodeB (eNB). In [15], the authors introduce a power and resource-sharing problem for vehicular communication, aiming to maximize the sum ergodic capacity of the V2I link while considering the latency violation probability (LVP) expressed through the effective capacity theory.

In [16], the authors put forward strategies for resource sharing concerning power allocation and channel assignment in a downlink situation specifically for D2D communication. In [17], authors investigate a heuristic space-matching method and develop a resource allocation strategy for D2D communication based on energy harvesting techniques underlying cellular networks. The authors in [18] propose an optimal resource allocation strategy to maximize the sum capacity of V2I users while satisfying the reliability requirement of V2V users. In [19], the authors propose a novel technique of joint power control and resource allocation to support safety related V2X communication. For lightly loaded network scenario, the authors propose Vacant Resource Blocks and Power Allocation algorithm (VRBPA) and Occupied Resource Blocks and Power algorithm (ORBPA)for heavily loaded network scenario.

To maximise the overall latency reduction in a vehicular ad hoc network (VANET), the authors in [20] offer resource-sharing strategies for selecting a group of V2V connections based on the cellular network and allocating sub-carriers to the users. The work concentrates on an overlay system that enables C-V2X and 802.11p communication between vehicles. A robust resource sharing and power allocation algorithm is discussed in [21] in order to ensure the extreme stability of V2V networks while optimising the overall capacity of V2I links. The authors in [23] propose a power control scheme to maximize the D2D throughput for an uplink channel in underlay 5G mm-wave network.

B. Contribution

In this paper, we investigate V2V communication in 5G cellular networks and propose a joint power control and resource sharing scheme for 5G V2X communication in cellular networks to improve spectrum efficiency and network performance. The main contributions of this paper are summarized as follows:

- A novel system model is proposed for V2X communication in a 5G underlying cellular network by maximizing the throughput of V2V users, while satisfying the reliability and latency requirement of V2I users.
- A novel power control and resource allocation scheme is developed to minimize the interference to V2V users. The work also considers the power and signal-to-interference noise ratio (SINR) constraint of V2V and V2I users.
- For spectrum efficiency, we present a system model where each V2V user can reuse the spectrum of the V2I user. The reuse pair matching problem is solved by a weighted bipartite matching method.

C. Organization

The paper is organised as follows. A detailed explanation of the system model is provided in Section II. The authors have formulated the system model in Section III. Section IV explains the resource allocation and power control strategy for the system model in detail. The simulation results are explained in Section V while Section VI concludes the work. Table I denotes the important notations used in the paper.

TABLE I
LIST OF IMPORTANT NOTATIONS

Symbol	Definition
I	Number of V2I user
J	Number of V2V user
f	Number of Resource Block(RB)
α	Path loss exponent
$\rho_{i,j}$	Binary indicator parameter for reusing the RB
$d_{j,j}$	Distance between V2V pair
$d_{i,j}$	Distance between V2I user and V2V pair
$d_{i,b}$	Distance between V2I user and BS
$d_{j,b}$	Distance between V2V pair and BS
$H_{i,b}$	Channel gain from i^{th} V2I user to BS
$H_{j,b}$	Channel gain from j^{th} V2V transmitter to BS
$H_{i,j}$	Channel gain between V2V pair and V2I user
p_i^I	Transmit power of i^{th} V2I user
p_j^V	Transmit power of j^{th} V2V pair
σ^2	Power of additive white Gaussian noise
Y_i	Signal to interference noise ratio (SINR) of i^{th} V2I user
Y_j	SINR of j^{th} V2V pair
Y_i^{min}, Y_j^{min}	Minimum SINR requirement of vehicular user
R_i^{min}, R_j^{min}	Minimum capacity requirement of vehicular user

II. SYSTEM MODEL

The work considers an uplink communication scenario representing the system model of a vehicular system in Fig 1. The system model comprises a high density of VUs that are arbitrarily and sporadically distributed. The system model assumes high mobility of VUs that causes Doppler effect to them. In such a scenario, the system model has relies only on the slowly varying large-scale channel parameters. V2I users facilitate the sharing of information among moving vehicles and road infrastructure, while V2V users are used for the exchange of information among various vehicles.

Here, we consider a single cell having a BS with a radius *R*. The system model considers *I* number of V2I users and *J* number of V2V pairs. The i^{th} V2I users are introduced by vehicles having an individual antenna that demands high capacity to facilitate applications that require significant bandwidth such as social networking and cloud access media streaming. The j^{th} V2V user is used by the vehicles to attain high reliability, in order to share safety-related messages between the neighbouring vehicles. To mitigate inter-channel interference, each V2I user is assigned a unique (orthogonal) channel in advance. The work represents a group of V2I users as $i = \{1, 2, ...I\}$ and V2V pairs as $j = \{1, 2...J\}$. The number of V2V users is typically greater than that of V2I users i.e. $j \gg i$ which is necessary for the V2V pair in case of spectrum reuse.

The signals received at the BS and V2V receiver are given by the following equations respectively:

$$y_i^I = \sqrt{P_i^I d_{i,b}^{-\alpha}} h_{i,b} s_i + \sqrt{P_j^V d_{j,b}^{-\alpha}} h_{j,b} s_j + \sigma^2 \quad (1)$$

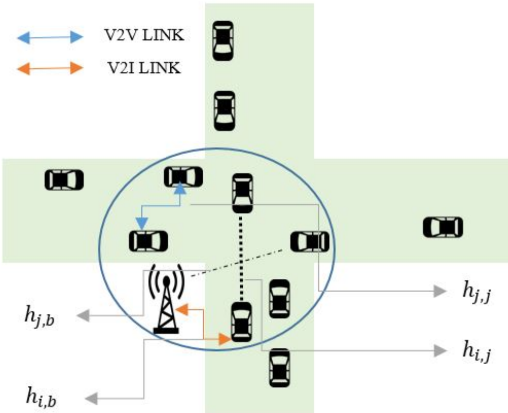

Fig. 1. System Model

$$y_j^V = \sqrt{P_j^V d_{j,j}^{-\alpha}} h_{j,j} s_j + \sqrt{P_i^I d_{i,j}^{-\alpha}} h_{i,j} s_i + \sigma^2 \quad (2)$$

The transmission power of i^{th} V2I user and j^{th} V2V pair is represented by P_i^I and P_j^V respectively. α represents the pathloss exponent. $d_{j,j}$, $d_{i,j}$, $d_{i,b}$ and $d_{j,b}$ denote the distances over $j \longrightarrow j$, $i \longrightarrow j$, $i \longrightarrow b$ and $j \longrightarrow b$ links respectively. $h_{j,j}$, $h_{i,j}$, $h_{i,b}$ and $h_{j,b}$ denote the small scale fading component over $j \longrightarrow j$, $i \longrightarrow j$, $i \longrightarrow b$ and $j \longrightarrow b$ links respectively. The spectrum reuse of the V2V link is given by indicator parameter $\rho_{i,j}$. Here, s_i and s_j represent the transmitted signal of V2I link and V2V receiver respectively whereas, σ^2 denote the additive white Gaussian noise power.

Due to the movement of vehicles, CSI used in V2V networks are significantly different from the actual channels during the transmission of data. The transmission of V2V links in this traffic congestion scenario can be represented using the Rayleigh channel fading model.

The signal-to-interference noise ratio (SINR) received at the BS for the i^{th} V2I user and j^{th} V2V link can be given by the following equations:

$$Y_i = \frac{P_i^I H_{i,b}}{\sum_{j=1}^{J} \rho_{i,j} P_j^V H_{j,b} + \sigma^2} \quad (3)$$

$$Y_j = \frac{P_j^V H_{j,j}}{\sum_{i=1}^{I} \rho_{i,j} P_i^I H_{i,j} + \sigma^2} \quad (4)$$

where $H_{i,b} = h_{i,b}^2 d_{i,b}^{-\alpha}$, $H_{j,b} = h_{j,b}^2 d_{j,b}^{-\alpha}$, $H_{j,j} = h_{j,j}^2 d_{j,j}^{-\alpha}$ and $H_{i,j} = h_{i,j}^2 d_{i,j}^{-\alpha}$.

The data rates of the i^{th} V2I user and j^{th} V2V pair is given by Shannon capacity theorem and can be written as:

$$R_i = B\, log_2(1 + Y_i) \quad (5)$$

$$R_j = B\, log_2(1 + Y_j) \quad (6)$$

III. PROBLEM FORMULATION

The main objective is to maximize the throughput of V2V users while maintaining the QoS of V2I users. The power and resource allocation problem can be formulated as:

$$max \sum_{j=1}^{J} B \log_2(1 + Y_j) \;\; \forall \;\; j \in J, \forall \;\; i \in I \quad (7)$$

subject to constraints:

$$C_1 : 0 \leq P_i^I \leq P_{max}^I \quad (8)$$

$$C_2 : 0 \leq P_j^V \leq P_{max}^V \quad (9)$$

$$C_3 : \rho_{i,j} \leq 1, \rho_{i,j} \in \{0, 1\} \quad (10)$$

$$C_4 : Y_i \geq Y_i^{min} \quad (11)$$

$$C_5 : Y_j \geq Y_j^{min} \quad (12)$$

$$C_6 : R_i \geq R_i^{min} \quad (13)$$

$$C_7 : R_j \geq R_j^{min} \quad (14)$$

Here, B denotes the bandwidth of the transmitted signal. In this scheme, the primary objective is to maximize the throughput of V2V pairs. According to the constraints C_1 and C_2, the transmission power of V2I links and V2V pairs should not exceed the maximum power limit. The constraint C_3 is a binary indicator parameter which represents the reuse of the resource of V2I users by V2V pairs. If the V2V pair reuses the spectrum of V2I users, then $\rho_{i,b} = 1$, otherwise 0. The constraints C_4 and C_5 signify that the SINR should be grater than minimum value to achieve proper communication between vehicles. Similarly, constraints C_6 and C_7 represent the minimum capacity requirement of both the users to maintain the QoS of both V2V pairs and V2I users.

IV. POWER CONTROL AND RESOURCE ALLOCATION

A. Power Control

In the following section, we will introduce a technique that aims to maximize system capacity by utilizing an optimal power strategy. We also explore the mechanism to introduce power control effectively in order to meet the requirement of maximum power limitation and minimum SINR for both V2I users and V2V pairs. When V2V pairs operate in reuse mode to communicate, they face co-channel interference from the V2I users. In order to get the maximum throughput of V2V communication, an optimal power approach is proposed while considering the minimum SINR and maximum transmit power limitation for both V2I user and V2V pairs, which is given by the following equation.

$$R(P_j^V, P_i^I) = max \;\; B \log_2 \left\{ \frac{P_j^V H_{j,j}}{\sum_{i=1}^{I} P_i^I H_{i,j} + \sigma^2} \right\} \quad (15)$$

subject to:

$$pr \left\{ Y_i \leq Y_i^{min} \right\} \;\; \leq \;\; p^o \quad (16)$$

$$P_i^I \leq P_{max}^I \;\; \forall \;\; i \quad (17)$$

$$P_j^J \leq P_{max}^J \;\; \forall \;\; j \quad (18)$$

For simplicity, we take the value of $B = 1$. $pr(.)$ represents the probability while p^o is the outage probability. It can be said from (15) that for a fixed value of P_i^I, the V2V capacity increases monotonically with P_j^V, and for a fixed value of P_j^V, the V2V capacity decreases monotonically with P_i^I. The optimal power can be calculated by solving the constraints (16) that satisfy the minimum SINR requirement for the V2I user in order to get the maximum V2V capacity which is shown below:

$$pr\Big\{Y_i \leq Y_i^{min}\Big\}$$
$$= 1 - \left(\frac{P_i^I \exp\Big(\frac{-Y_i^{min}\sigma^2}{P_i^I}\Big)}{P_i^I + P_j^V Y_i^{min}} \right) \leq \ p^o \tag{19}$$

The optimal power for V2V pair can be found by equating (19) to zero and the calculation is as follows:

$$P_j^{V^*} = \frac{P_i^I}{Y_i^{min}} \Big(\frac{\exp\Big(\frac{-Y_i^{min}\sigma^2}{P_i^I}\Big)}{1 - p_o} - 1 \Big) \tag{20}$$

which is a function of P_i^I. The optimal power for V2I user can be calculated by considering $P_j^{V^*} \geq 0$ and is expressed as follows:

$$P_i^{I^*} = \frac{-Y_i^{min}\sigma^2}{ln(1 - p^o)} \tag{21}$$

It can be observed from (20) that $P_j^{V^*}$ is a function of (P_i^I) that monotonically increases with respect to V2I power.

B. Resource Allocation

The optimal capacity of the j^{th} V2V pair is denoted by R_j^* that reuses the spectrum of the i^{th} V2I user. The optimal power allocation can be obtained from equation (20) and (21) for the frequency reuse of i^{th} V2I user and j^{th} V2V pair which leads to maximum capacity of the j^{th} V2V pair denoted by $R_j(P_i^{I^*}, P_j^{V^*})$ thereby, maintaining the reliability and latency requirement of V2I user.

However, $R_j(P_i^{I^*}, P_j^{V^*})$ being the maximum capacity may not meet the minimum capacity R_j^{min} requirement for V2V communication. Therefore, the proposed power allocation removes the limitation of the V2V pair capacity. Also, reuse pair is not feasible in this situation. In order to consider the minimum capacity of V2V pair into account, an expression is formulated for the frequency reuse pattern shown below:

$$R_j^* = \begin{cases} R_j(P_i^{I^*}, P_j^{J^*}) & , \ if \ \ R_j(P_i^{I^*}, P_j^{V^*}) \geq R_j^{min} \\ 0 & , \ otherwise \end{cases} \tag{22}$$

In order to identify the best reuse pattern, the final step is to solve the weighted bipartite matching problem :

$$max \sum_{j=1}^{J} B \log_2(1 + Y_j) \ \forall \ j \ \in \ J, \forall \ i \in \ I \tag{23}$$

subject to:

$$\sum_{i=1}^{I} \rho_{i,j} \leq 1, \rho_{i,j} \in \ \{0,1\} \ \forall \ i \in \ I \tag{24}$$

$$\sum_{j=1}^{J} \rho_{i,j} \leq 1, \rho_{i,j} \in \{0,1\} \ \forall \ j \in \ J \tag{25}$$

which may be effectively solved by the Hungarian Method in polynomial time [17]. Hungarian method is an optimization technique that solves optimization problem in polynomial time, and used for efficient matching.

It is important to emphasize that the resource allocation scheme proposed in this paper has the capability to identify the globally optimal solution. This is achieved by selecting the most suitable reuse pattern from all available options, taking into consideration their optimal power allocations. For every i^{th}, j^{th} feasible V2V pair, the degree of complexity for power allocation is $O(i * jlog(\frac{1}{\epsilon}))$where the bisection search's error tolerance is ϵ. The optimisation spectrum sharing structure is solved by the Hungarian method within $O(j^3)$ time. As a result, the overall complexity of the developed algorithm is $O(i * j \log(\frac{1}{\epsilon}) + j^3)$.

TABLE II
SIMULATION PARAMETERS

Parameters	Value
Carrier frequency	2 GHz
Bandwidth	10 MHz
Cell radius	500 m
BS antenna height	25 m
BS antenna gain	8 dBi
Vehicle antenna height	1.5 m
Vehicle antenna gain	3 dBi
Number of V2I users	20
Number of V2V users	20
Maximum V2I transmit power (P_{max}^I)	23 dBm
Maximum V2V transmit power (P_{max}^V)	23 dBm
Noise power (σ^2)	-114 dBm
SINR threshold of V2V (Y_i^{min})	-4 dB
Outage probability p^o	10^{-3}

C. Analysis of Outage Probability

Outage probability refers to the probability that the received signal quality falls below a certain predefined threshold, resulting in a loss of reliable communication i.e.:

$$pr\{Y_i \leq Y_i^{min}\}$$
$$= pr\Big\{\frac{P_i^I H_{i,b}}{P_j^v H_{j,b} + \sigma^2} \leq Y_i^{min}\Big\}$$
$$= 1 - \left(\frac{P_i^I \exp \frac{-Y_i^{min}\sigma^2}{P_i^I}}{P_i^I + P_j^V Y_i^{min}} \right) \tag{26}$$

V. NUMERICAL RESULTS

In this section, we provide the simulation results of our investigation, which aims to improve the throughput of V2V users while maintaining the QoS of V2I users. In this section, we examine the effectiveness of our proposed approach by considering the various factors such as throughput SINR of V2V pairs and V2I users. We also consider the Cumulative Distribution Function (CDF) of V2V users and compare the results with reference [18] for the validation of our work. The simulation parameters used in our study are mentioned

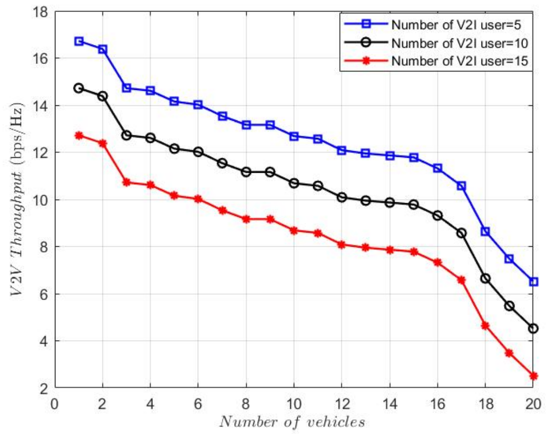

Fig. 2. Throughput of V2V versus number of vehicles for different number of V2I users

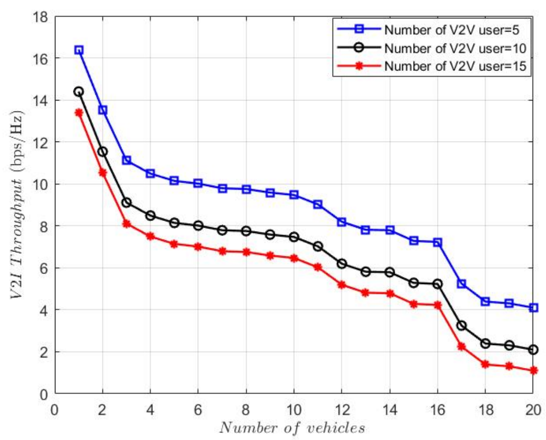

Fig. 3. Throughput of V2I versus number of vehicles for different number of V2V users

in Table II. Fig. 2. represents the V2V throughput versus different numbers of vehicles for a fixed number of V2I users, respectively. In Fig. 2. the throughput of the V2V pair decreases as the number of vehicles increases. This is because the increase in the number of vehicles leads to an increase in interference which eventually degrades the performance. Also for a fixed V2I, the capacity improves when number of the V2I users is less. This is because the interference will increase with the increase in V2I users. Similarly Fig. 3. represents the V2I throughput with the increase in the number of vehicles for a fixed number of V2V users. The throughput of the V2I user decreases with an increase in the number of vehicles since the increase in the number of vehicles leads to an increase in interference, which degrades the performance. Also for a fixed number of V2I users, the capacity decreases as the number of V2V pair increases. This is because the increase in the number of V2V pairs leads to an increase in interference which affects the throughput. It can be also seen that the throughput of V2V users is high as compared to V2I users. Fig. 4 and Fig. 5. exhibit the relationship between

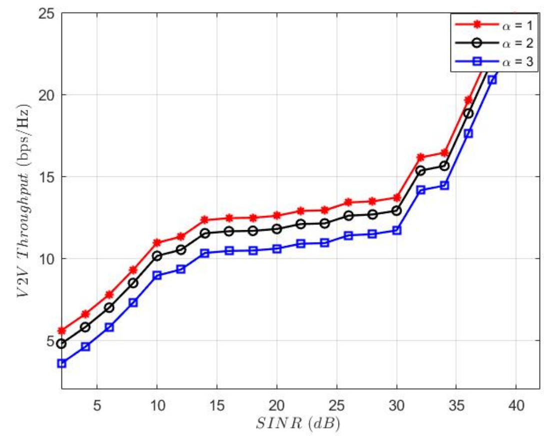

Fig. 4. Throughput of V2V versus SINR

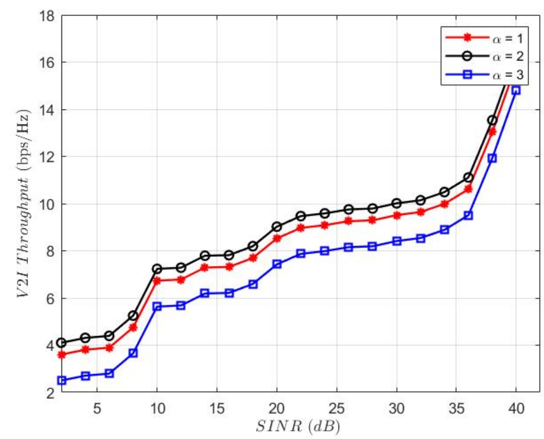

Fig. 5. Throughput of V2I versus SINR

throughput and SINR for different values of pathloss exponent (α) for V2V and V2I users respectively. It is shown that the throughput is high for $(\alpha = 1)$ and less for $(\alpha = 3)$. The reason is that the pathloss exponent specifies that the signal power declines rapidly with the increase in distance. When the value of the pathloss exponent is less than the signal strength, it decreases at a slower rate with an increase in the distance while the capacity of the system increases. When the value of the pathloss exponent is high, signal power decreases more rapidly with an increase in distance and as a result, the capacity of the system decreases.

Fig. 6. represents the CDF versus SINR of V2V users in terms of outage probability. Each V2V user has a target SINR threshold of 4 dB which is approximately satisfied from this figure. The value of SINR in [18] and in [22] is 5 dB for $p^o = 10^{-3}$. While in the proposed work, SINR is 4 dB for $p^o = 10^{-3}$. This shows the effectiveness of our proposed scheme.

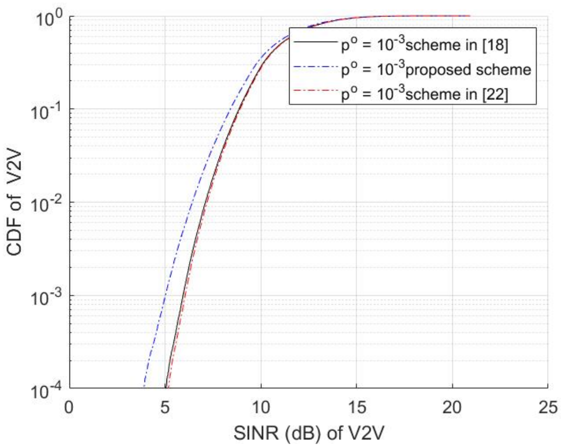

Fig. 6. CDF versus SINR of V2V

VI. CONCLUSION

In this work, a frequency reuse scheme is introduced to mitigate interference in V2X communication, specifically between V2V and V2I users in 5G networks. A weighted bipartite matching technique is proposed for the optimal selection of reuse pair that is solved by the Hungarian method. Also, the throughput of V2V and V2I users is evaluated for different number of vehicles. The variation in throughput of the V2V pair and V2I link is examined for different SINR values. The CDF curve for the proposed scheme is evaluated for the SINR at a particular outage probability and is also compared with the existing scheme in [18] which proves the effectiveness of our work. The simulation results demonstrate that the proposed scheme yields considerable performance and is effective for V2X communication.

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