Optimum Resource Allocation for Full-Duplex Vehicular Communication Networks

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ABSTRACT In this article, we propose a resource allocation (RA) scheme for vehicular communication networks (VCNs). The proposed scheme exploits the spectral efficiency of full-duplex (FD) communications to fulfill the reliability constraints of vehicle-to-vehicle (V2V) links and the high capacity requirements of vehicle-to-infrastructure (V2I) links. Also, it is capable of coping with the fast variations of the channels due to the high mobility. Based on the links requirements, the RA problem is formulated as a non-convex problem, which is solved in two steps. First, the optimal power allocation (PA) is obtained by solving a system of linear equations. Second, the channel assignment (CA), which turns out to be a maximum weight bipartite matching problem, is solved using the Hungarian method. Also, a heuristic hybrid scheme, which combines the proposed FD scheme and the half-duplex (HD) scheme that optimally finds the RA, is proposed. Compared to the optimal HD-based scheme, simulation results show that the proposed FD scheme always offers higher sum of the V2I links’ capacities except for the case in which V2V links require low transmission rates, while the hybrid scheme ensures higher performance for all potential cases.

INDEX TERMS Vehicular communications, full-duplex, power allocation, spectrum sharing, links requirements.

I. INTRODUCTION Vehicular communication networks (VCNs) have attracted a lot of attention due to their ability to improve road safety and traffic control as well as support advanced infotainment applications [1]. Multiple industry standards related to vehicular communications such as the IEEE 802.11p, utilizing the dedicated short range communications (DSRC), and the intelligent transportation system (ITS)-G5 [2] have been introduced. Most recently, the 3rd Generation Partnership Project (3GPP) has initiated projects to provide vehicle-to-everything (V2X) services in the widely deployed long term evolution (LTE) cellular networks [3], [4]. Recent studies in LTE cellular networks supported with device-to-device (D2D) underlay communications have shown great potential for improving the performance of V2X services in terms of coverage, resource management, dealing with high mobility and channel capacity [4]. Such V2X communications will at least encompass two equally important communication scenarios, namely vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V), which are of interest in this article.

The nature of the information exchanged over V2V and V2I links is what defines the links requirements that must be fulfilled. For example, traffic safety applications of V2V links entail high communication reliability, while infotainment applications of V2I links necessitate high data capacity [1], [5]. Another important difference between resource allocation (RA) for LTE cellular networks and that for VCNs is that the RA schemes proposed for the former (e.g., [6], [7]) traditionally depend on the acquisition of full channel state information (CSI). However, frequent reporting of the fast varying CSIs of high-mobility vehicles to base stations (BSs) in VCNs may cause significant overhead. Therefore, in addition to the quality-of-service (QoS) requirements of the links,
the nature of the VCNs channels has also been considered in the recent RA schemes such as [8]–[12]. These half-duplex (HD) RA schemes are designed based on either large-scale fading parameters solely or on both large-scale fading of all links and statistical information of the small-scale fading of V2V links such as in [12] and [5], respectively. Exploiting statistical information of small-scale fading leads to more accurate results as well as avoiding reporting overhead of instantaneous CSI [5].

In-band full-duplex (FD) communications, where nodes can transmit and receive simultaneously over the same band, can achieve high spectral efficiency as opposed to HD communications. Recently, the impressive improvement in the self-interference cancellation (SIC) techniques (e.g., 70 ∼ 110 dB) has attracted a lot of attention to in-band FD communication as a promising technology for future wireless systems [13]. For VCNs, in particular, there is a great potential for using FD communications where requirements such as the need for space for antenna isolation and for an on-board unit with high computational efficiency as well as energy consumption considerations are less challenging to be satisfied in vehicles than in mobile devices [13]. Our goal is to exploit the spectral efficiency of FD communications in V2V links to enhance the performance of both V2I and V2V links.

In the RA of LTE cellular networks, the integration of in-band FD communications in D2D links has been widely studied in the literature [14]–[20]. Due to the short range of D2D links, D2D devices require low transmit powers, which makes them perfect candidates to exploit the spectral efficiency of FD communications. This is because the low transmit powers lead to weak self-interference (SI) [14]–[16]. However, none of the reported FD D2D works has been proposed for VCNs. Accordingly, they do not fulfill the aforementioned requirements of V2I and V2V links, which must be fulfilled by any proposed RA for VCNs [5]. The desire to fill this gap by exploiting the spectral efficiency of FD communications to fulfill the QoS requirements of the links was the main motivation for this work.

In this article, we propose an RA scheme for FD VCNs. The proposed scheme considers the nature of the VCN channel and QoS requirements of the V2I and V2V links. It is designed based on the large-scale fading parameters and statistical information of the small-scale fading of the V2V links to avoid the overhead of frequent reporting of the CSIs to the BS. To fulfill the high capacity requirement of the V2I links, the sum of their capacities is maximized. The reliability constraints of the V2V links are guaranteed by keeping their outage probabilities below a small tolerable threshold.

The optimization problem that fulfills the aforementioned requirements is formulated as a non-convex problem and it is solved in two steps by finding the power allocation (PA) first, followed by the channel assignment (CA). Two optimal solutions of the PA problems are presented. First, the PA problem is formulated as a geometric program (GP) and optimally solved using the interior-point method. In spite of its relative complexity, this solution is characterized by its flexibility for modifications (e.g., adding constraints and/or changing the objective function to maximize the sum of the capacities of the V2I and V2V links instead) as will be discussed in Section V. Second, by proving that the optimality occurs when the reliability constraints of the V2V links are met with equality, an efficient and optimal solution of the PA is obtained by solving a system of linear equations. The CA problem is then solved efficiently using the Hungarian method [21].

In addition, a heuristic hybrid scheme, which merges the proposed FD scheme with the HD one in [1] that optimally finds the RA is proposed. FD communications offer near twice the spectral efficiency of HD communications. However, using FD communications in V2V links introduces more interference. Therefore, it is not necessary that FD communications always offer better performance. Based on our spectrum sharing assumptions and clustering scheme of V2V links, there is no inter-cluster interference as will be discussed in Section V. The proposed hybrid scheme determines whether using FD or HD communications in the V2V links is better for each cluster independently of other clusters. As compared to the proposed FD scheme and the HD scheme in [1], the hybrid scheme ensures better performance at the price of a slight increase in computational complexity that yet remains within the same complexity order.

The remainder of this article is organized as follows. An overview of the related work is presented in Section II. The system model is introduced in Section III. Section IV discusses the problem formulation that fulfills the links requirements. In Section V, the proposed FD RA scheme is introduced, where the PA and the CA are discussed. Section VI then introduces further insights and extensions where a proposed FD/HD hybrid scheme, a proposed slow-fading based resource allocation scheme followed by complexity analysis of the proposed schemes are presented. The performances of the proposed schemes are evaluated based on simulations in Section VII. Finally, conclusions are presented in Section VIII.

II. RELATED WORK

The RA of VCNs has been widely investigated in the literature under different spectrum sharing and channel state acquisition assumptions. In all these RA schemes, HD communication is adopted. In this section, we present an overview of most related work.

A heuristic RA scheme is presented in [10], where V2V links reuse the spectrum of the cellular uplinks. The cell coverage is split into set of zones. Based on the spatial information of vehicles, the spectrum reuse of each zone is assigned such that the interference in the uplinks will not exceed a certain threshold. In [9], assuming full CSI acquisition, the PA that maximizes the minimum achievable rate of V2V links is found. To reduce the overhead caused by the exchange of full CSI, suboptimal solution based on vehicles locations is presented. In [8], a joint PA and mode selection is proposed. Based on links quality, this scheme
determines whether V2V links or traditional cellular links is better for communication between two vehicles. Two metrics are adopted for mode selection, in particular, outage probability and system throughput. The work in [11] has considered latency and reliability requirements of V2V links as well as high capacity requirements of V2I links. The sum of V2I links capacities is maximized under the reliability constraints of V2V links, which in turn is fulfilled by ensuring that the outage probabilities of V2V links are less than acceptable threshold. On the other hand, latency requirements are met by allowing V2V links to reuse multiple resource blocks (RBs) simultaneously such that the required transmission rate can be met within the delay bound. As the number of V2V links is much larger than that of V2I links, the author of [11] has extended their work in [12] such that multiple V2V links can share the same RB.

Unlike the aforementioned RA schemes in [8]–[12] that have been designed based on large-scale fading parameters only, the RA schemes in [5], [22] and [1] are developed based on large-scale fading parameters as well as statistical information of small-scale fading of V2V links. Accordingly, they reflect more accurate results of the system performance as well as avoiding frequent reporting of the fast varying CSIs of high-mobility vehicles in V2V links to the BSs. In [5], the sum of the ergodic capacities of V2I links is maximized under the consideration of the reliability requirements of V2V links. In [22], the RA problem of [5] is studied under the assumption of outdated CSI feedback. The RA scheme in [1] fulfilled the links requirements by maximizing the sum of the V2I links capacities while ensuring that the outage probabilities of V2V links remain below small threshold. Unlike the scheme in [5], multiple V2V links can share the same RB concurrently.

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B. CHANNEL MODEL

In the $m$-th V2I link, the channel gain between the vehicle of this link and the BS is given by [23]

$$h_m = g_m u_m,$$  \hspace{1cm} (1)

where $u_m$ models the small-scale fading channel power. Assuming Rayleigh fading, $u_m$ is modelled by an exponentially distributed random variable with unit mean as in [23]. $g_m$ represents the large-scale fading component that encompasses shadowing and path-loss. Since the distances of the links do not change much within the time slot duration, the path-loss can be treated as constant. Also, the shadowing does not change much [23]. Therefore, similar to the schemes in [1], [5] and [12], we assume that $g_m$ is constant within the time slot duration. All the remaining channels of the network are assumed to be similar to $h_m$ with their definitions given in Table 1 where $j$ indicates the $j$-th V2V pair that reuses the $m$-th RB. Henceforward, the symbol $B$ is used in the superscript to denote the BS, while $c$ is used to denote the vehicle in the V2I link since it uses the cellular uplink. Also, the vehicles in each V2V pair are denoted by vehicle 1 and vehicle 2 to distinguish between them as expressed in channel definitions of V2V links in Table 1.

We assume that the BS has the large-scale information of all links (i.e., shadowing and path-loss) that depend on the vehicles locations and that are characterized by a slow rate of change. Also, the BS is capable of estimating the instantaneous channels of the V2I links and the interfering links from vehicles in V2V links. As the BS is at the receiving end of these links, exploiting instantaneous channel information will not cause overhead. Meanwhile, statistical parameters of the V2V and SI links can be estimated by the receivers of these links and fed back periodically to the BS. To achieve that, the channel gains are measured over a relatively long time period such that the small scale fading effects are averaged out [12]. These average values are then reported from the vehicles in V2V pairs to the BS instead.

III. SYSTEM MODEL

A. NETWORK MODEL

For simplicity, we consider a single cell VCN that consists of a set $\mathcal{M} = \{1, 2, \ldots, M\}$ of V2I links and a set $\mathcal{N} = \{1, 2, \ldots, N\}$ of V2V ones as illustrated in Fig. 1. We assume that each vehicle is equipped with two isolated antennas for transmission and reception. Also, HD communication is assumed for V2I links, while FD communication is considered for the V2V links. The bandwidth of the uplink, which is the focus of this work, is split into $M$ equal RBs, where each V2I link is served by a single RB (i.e., no interference among the V2I links). To improve the spectral efficiency, the uplink spectrum of the V2I links is reused by the V2V links as the usage intensity of the uplink resources is typically less than that of the downlink [5]. In practice, as the number of V2V pairs, $N$, is much larger than the number of V2I links $M$ ($N \gg M$) [1], we assume that each RB can be reused by multiple V2V pairs. The V2V pairs that reuse the same RB form a cluster where the $n$-th cluster, $n \in \mathcal{N}_C = \{1, 2, \ldots, N_C\}$, is represented by the set $C_n$ and the number of V2V pairs belonging to it is denoted by $N_{C_n}$. Details pertaining to cluster formation will be discussed later in this section.

![FIGURE 1. A schematic of the considered vehicular communication network that consists of $M$ V2I links and $N$ V2V links.](image-url)
TABLE 1. Definitions of the network channels.

| Symbol | Channel Definition |
|--------|--------------------|
| $h_m$  | The channel of the $m$-th V2I link |
| $h_{m,i}^{1,1}$ | The channel between the transmitting vehicle of the $m$-th V2I link and vehicle 1 (vehicle 2) of the $i$-th V2V pair |
| $h_{m,i}^{1,2}$ | The channel between the receiving vehicle of the $m$-th V2I link and vehicle 1 (vehicle 2) of the $i$-th V2V pair |
| $h_{m,i}^{2,B}$ | The interfering channel from vehicle 1 (vehicle 2) of the $j$-th V2V pair to the BS |
| $h_{m,i}^{1,1}$ | The channel between vehicle 1 (vehicle 2) of the $i$-th V2V pair and vehicle 2 (vehicle 1) of the $m$-th V2V pair |
| $h_{m,i}^{1,2}$ | The channel between vehicle 1 (vehicle 2) of the $i$-th V2V pair and vehicle 1 (vehicle 2) of the $m$-th V2V pair |
| $h_{j}^{SI,1}$ | The SI channel of vehicle 1 (vehicle 2) of the $j$-th V2V pair |

of the instantaneous CSI. As the BS only tracks the statistical information of the small-scale fading of the V2V links, it avoids the overhead of transmitting instantaneous CSI that is characterized by a rapid rate of change due to the vehicles mobility.

Based on the stated assumptions, the signal-to-interference-plus-noise-ratios (SINRs) of the $m$-th V2I link is equal to

$$
\gamma_m^c = \frac{P_{c,n,m} h_m}{\sum_{j \in C_n} P_{1,1}^{m,j} h_{m,j}^{1,B} + \sum_{j \in C_n} P_{2,1}^{m,j} h_{m,j}^{2,B} + \sigma^2},
$$

where the denominator consists of the interference signals from the FD V2V pairs in the cluster $C_n$ that reuse the $m$-th RB as well as the additive white Gaussian noise (AWGN) average power $\sigma^2$. In (2), $P_{c,n,m}$ is the transmit power of the vehicle in the $m$-th V2I link when the $m$-th RB is reused by the $n$-th cluster $C_n$, while $P_{1,1}^{m,j}$ ($P_{2,1}^{m,j}$) is that of vehicle 1 (vehicle 2) of the $j$-th interfering V2V pair. The received SINR of the link from vehicle 1 to vehicle 2 of the $l$-th V2V pair is similar to the $m$-th RB, where $\beta$ is the SIC factor. As the SI cannot be perfectly removed, $\beta$ is used to represent the residual SI, where $0$ $\leq \beta$ $\leq 1$. The denominator in (3) consists of the interference due to SI, the $m$-th V2I link, the FD V2V pairs in the same cluster $C_n$ that reuse the $m$-th RB in addition to the AWGN power. Likewise, the received SINR of the link from vehicle 2 to vehicle 1 of the $l$-th V2V pair is equal to

$$
\gamma_l^{m,l} = P_{c}^{m,l} h_{l,1}^{1,2} \left( \frac{\beta P_{1}^{m,l} h_{l,1}^{SI,2} + P_{c}^{m,l} h_{l,1}^{c,2}}{\sum_{j \in C_n \backslash l} (P_{1}^{m,j} h_{j,1}^{1,2} + P_{2}^{m,j} h_{j,1}^{2,2})} + \sigma^2 \right),
$$

where $\beta$ is the SIC factor. As the SI cannot be perfectly removed, $\beta$ is used to represent the residual SI, where $0$ $\leq \beta$ $\leq 1$. The denominator in (3) consists of the interference due to SI, the $m$-th V2I link, the FD V2V pairs in the same cluster $C_n$ that reuse the $m$-th RB in addition to the AWGN power. Likewise, the received SINR of the link from vehicle 2 to vehicle 1 of the $l$-th V2V pair is equal to

$$
\gamma_l^{m,l} = P_{c}^{m,l} h_{l,1}^{1,2} \left( \frac{\beta P_{1}^{m,l} h_{l,1}^{SI,2} + P_{c}^{m,l} h_{l,1}^{c,2}}{\sum_{j \in C_n \backslash l} (P_{1}^{m,j} h_{j,1}^{1,2} + P_{2}^{m,j} h_{j,1}^{2,2})} + \sigma^2 \right),
$$

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C. CLUSTERING ALGORITHM

The V2V pairs in the system are clustered into $N_c$ clusters, where the members of each cluster $C_n$, $n \in \{1, 2, \cdots, N_c\}$, share the same RB with a specific V2I link. Consequently, the number of clusters $N_c$ is equal to the number of V2I links $M$. In this work, clustering is formed such that the mutual interference between the V2V pairs in each cluster is minimized. In [1], a heuristic algorithm, based on the max $N$-cut method [24], that minimizes the intra-cluster interference is presented. We adopt this clustering scheme but with slight modifications related to the computation of the mutual interference since in FD communications more interference exists between the links. This modified heuristic algorithm is summarized in Algorithm 1. This algorithm results in $N_c$ clusters, each of which may have a different number of V2V pairs.

Algorithm 1 Clustering Algorithm

1. Randomly choose $M$ V2V pairs and assign each one of them to one of the $N_c$ clusters.
2. Add the $M$ selected pairs to the empty set $\mathcal{Y}$.
3. while $|\mathcal{Y}| < N$ do
4. Choose an unassigned V2V pair $l$, where $l \in N$ and $l \notin \mathcal{Y}$.
5. Find the sum of the intra-cluster interference of each of the $M$ clusters after adding the $l$-th V2V pair using

$$
\sum_{j \in C_n} (g_{j,1}^{1,1} + g_{j,1}^{2,1} + g_{j,1}^{2,2}) + 2 \sum_{j \in C_n} g_{j,1}^{1,2} + g_{j,1}^{2,1} + g_{j,1}^{2,2}.
$$

6. Add the $l$-th V2V pair to the $n$-th cluster with minimum sum in Step 5.
7. end while

Although the proposed clustering algorithm may seem too heuristic, it is in fact very effective in improving the performance. By minimizing the intra-cluster interference, the V2V pairs can fulfill their reliability constraints using less transmission powers (i.e., $P_{1}^{m,j}$ and $P_{2}^{m,j}$) or allow for more interference from the V2I link that uses the same RB. From (2), since $\gamma_m^c$ increases (decreases) monotonically with $P_{c,n,m}^{m,j}$ ($P_{1}^{m,j}$ and $P_{2}^{m,j}$), decreasing the intra-cluster interference through the proposed clustering improves the system performance in terms of the V2I links capacities as will be assessed in Section VII.

IV. PROBLEM FORMULATION

The nature of the information exchanged in V2V links (e.g., traffic safety applications) necessitates high communication reliability [1], [5], [12]. This could be met by ensuring that the outage probabilities of the V2I links are less than an acceptable small threshold. For the $l$-th V2V link, the outage probability constraints are given by

$$
\text{Prob} \left\{ \gamma_l^{m,l} \leq \gamma^s \right\} \leq O_l^r,
$$

$$
\text{Prob} \left\{ \gamma_1^{m,l} \leq \gamma^s \right\} \leq O_l^r.
$$
where $\gamma^v$ is the SINR threshold of the FD V2V links required to achieve a specific rate $R_v$ and $O^v_j$ is the maximum allowed outage probability of the $l$-th V2V pair. On the other hand, to fulfill the high capacity requirements of the V2I links, we choose to maximize the sum of the capacities of the V2I links.

The RA problem of the VCN under consideration assigns each of the $N_C$ clusters to one of the $M$ V2I links to share the RB with. In addition, it determines the transmission powers of all vehicles in V2I and V2V links. This is all done while fulfilling the QoS requirements of the links. The RA problem can now be formulated as

$$\max \left\{ \sum_{n=1}^{N_C} \sum_{m=1}^{M} a_{n,m} R_{n,m} \right\}$$

subject to

$$\prob \left[ \gamma^m_{1,j} \leq \gamma^v \right] \leq O^v_j, \quad \forall m \in M, \ \forall j \in C_n, \forall n \in N_C,$$

$$\prob \left[ \gamma^m_{2,j} \leq \gamma^v \right] \leq O^v_j, \quad \forall m \in M, \ \forall j \in C_n, \forall n \in N_C,$$

$$0 < P^c_{n,m} \leq P^c_{\max}, \quad \forall m \in M, \ \forall n \in N_C,$$

$$0 < P^m_{n,m} \leq P^m_{\max}, \quad \forall m \in M, \ \forall j \in C_n, \forall n \in N_C,$$

$$0 < P^v_{n,m} \leq P^v_{\max}, \quad \forall m \in M, \ \forall j \in C_n, \forall n \in N_C,$$

$$\sum_{n=1}^{N_C} \sum_{m=1}^{M} a_{n,m} \leq 1, \ a_{n,m} \in \{0, 1\}, \ \forall m \in M,$$

$$\sum_{m=1}^{M} a_{n,m} \leq 1, \ a_{n,m} \in \{0, 1\}, \ \forall n \in N_C,$$

where $R_{n,m}$ is the capacity of the $m$-th V2I when the $n$-th cluster reuses the spectrum of the $m$-th RB, and is given by

$$R_{n,m} = \log_2 \left( 1 + \frac{P^c_{n,m} h_m}{\sum_{j=1}^{N_{CS}} \left( P^{m,j}_{1,h_{1,m}} + P^{m,j}_{2,h_{2,m}} \right) + \sigma^2} \right).$$

The constraints in (7b) and (7c) ensure the reliability of the two links of each V2V pair. The constraints in (7d) and (7e)-(7f) set the maximum allowed transmit powers for V2I and V2V links, given by $P^c_{\max}$ and $P^m_{\max}$, respectively. The assumptions that an RB can be reused by one cluster only and the V2V pairs of a cluster can share the spectrum of a single RB are ensured by (7g) and (7h) through the binary decision variable $a_{n,m}$, which is equal to 1 (0) when the RB of the $m$-th V2I link is reused (not reused) by the $n$-th cluster.

V. PROPOSED RESOURCE ALLOCATION SCHEME

The combinatorial nature of the problem in (7) as well as the existence of the integer variables $\{a_{n,m}\}$ make it difficult to find a direct solution. Instead, the RA problem in (7) will be solved in two steps. Since the constraints in (7g) and (7h) ensure that interference only exists between the $m$-th V2I link and the $n$-th cluster that reuses the $m$-th RB (i.e., there is no interference with the other V2I links or other clusters), the PA of the vehicle in the $m$-th V2I link and the vehicles of the V2V pairs in the $n$-th cluster can be found independently of other V2I links and clusters. Accordingly, the RA problem can be decomposed into a PA and CA problems. First, we will determine the PA of each cluster with each of the $M$ V2I links. In each of the $N_C \times M$ combinations of the $N_C$ clusters and $M$ V2I links, the computed optimal transmission powers are used to determine the capacity $R_{n,m}$ that is given by (8). Then, we will find the CA, in which each of the $N_C$ clusters will be assigned to one of the $M$ V2I links to share the RB with. The CA is performed such that the sum of the capacities of the V2I links is maximized. The details of the two allocation problems are provided as follows.

A. POWER ALLOCATION

In this subsection, we introduce an optimal solution for the PA problem based on the interior-point method. In Section V-C, we present an alternative low-complexity approach for solving this problem as well. For the $m$-th V2I link and the $n$-th cluster that reuses the $m$-th RB, the PA problem can be formulated as

$$\max \left\{ \sum_{l \in C_n} \left( \frac{P^c_{n,m} h_m}{P^m_{1,1} h_{1,m,l} + P^m_{2,1} h_{2,m,l} + \sigma^2} \right) \right\}$$

subject to

$$\prob \left[ \gamma^m_{1,l} \leq \gamma^v \right] \leq O^v_l, \quad \forall l \in C_n,$$

$$\prob \left[ \gamma^m_{2,l} \leq \gamma^v \right] \leq O^v_l, \quad \forall l \in C_n,$$

$$P^c_{\min} < P^c_{n,m} \leq P^c_{\max},$$

$$P^m_{\min} < P^m_{n,m} \leq P^m_{\max},$$

$$P^v_{\min} < P^v_{n,m} \leq P^v_{\max}, \quad \forall l \in C_n.$$
expressed as in (9c) can be simplified and the problem in (9) can now be threshold outage probability in the left side of (12) will be replaced by two constraints that basically apply the same probability in the left side of (12) is given by

\[
1 - \exp \left( -\frac{\gamma' \sigma^2}{P_{1}^{m,l} g_{1,l}} \right) \leq O_{y},
\]

\[
\times \prod_{j \in C_n \setminus I} \frac{1}{1 + \frac{\gamma' P_{j}^{m,l} g_{j,l}^2}{P_{1}^{m,l} g_{1,l}^2}} \leq O_{y},
\]

\[
\times \prod_{j \in C_n \setminus I} \frac{1}{1 + \frac{\gamma' P_{j}^{m,l} g_{j,l}^2}{P_{1}^{m,l} g_{1,l}^2}} \leq O_{y},
\]

where \( E[\cdot] \) returns the expected value. Since large-scale fading parameters are assumed to be fixed within the time slot and small-scale fading are modelled by exponentially distributed random variables with unit mean as mentioned in Section III, the constraint in (11) can be written as

\[
1 - \exp \left( -\frac{\gamma' \sigma^2}{P_{1}^{m,l} g_{1,l}^2} \right) \leq O_{y},
\]

\[
\times \prod_{j \in C_n \setminus I} \frac{1}{1 + \frac{\gamma' P_{j}^{m,l} g_{j,l}^2}{P_{1}^{m,l} g_{1,l}^2}} \leq O_{y},
\]

\[
\times \prod_{j \in C_n \setminus I} \frac{1}{1 + \frac{\gamma' P_{j}^{m,l} g_{j,l}^2}{P_{1}^{m,l} g_{1,l}^2}} \leq O_{y},
\]

where \( E \left[ P_{1}^{m,l} g_{1,l}^2 \right] = P_{1}^{m,l} g_{1,l}^2 \) [23]. Similarly, the other expected values in (11) can be found as expressed in (12). In [26], the upper and lower bounds of the outage probability in the left side of (12) are found. The upper bound of the outage probability in the left side of (12) is given by

\[
1 - \exp \left( -\frac{\gamma' \sigma^2}{P_{1}^{m,l} g_{1,l}^2} \right) \leq O_{y},
\]

\[
\times \prod_{j \in C_n \setminus I} \frac{1}{1 + \frac{\gamma' P_{j}^{m,l} g_{j,l}^2}{P_{1}^{m,l} g_{1,l}^2}} \leq O_{y},
\]

\[
\times \prod_{j \in C_n \setminus I} \frac{1}{1 + \frac{\gamma' P_{j}^{m,l} g_{j,l}^2}{P_{1}^{m,l} g_{1,l}^2}} \leq O_{y},
\]

\[
\times \prod_{j \in C_n \setminus I} \frac{1}{1 + \frac{\gamma' P_{j}^{m,l} g_{j,l}^2}{P_{1}^{m,l} g_{1,l}^2}} \leq O_{y},
\]

In the typical area of interest of the outage probability (i.e., in the order of \( O_{y} \) \( 10% \)), the lower and upper bounds are soft and the difference between them almost vanishes (for more information about the tightness of the bounds, please refer to [23, Fig. 1] and [26]). Hence, inspired by [1], the outage probability in the left side of (12) will be replaced by its upper bound in (13). Replacing the outage probability in (12) with its upper bound ensures that the highest outage probability that may occur still remains below the acceptable threshold \( O_{y} \). Similarly, the outage probability constraints in (9c) can be simplified and the problem in (9) can now be expressed as

\[
\min_{\{P_{n,m}^{m,l}, P_{m,l}^{m,l} \}} \sum_{l \in C_n} \left( \frac{P_{1}^{m,l} h_{1,m,l} + P_{2}^{m,l} h_{2,m,l}}{P_{c}^{m,l} h_{m}} \right) + \sigma^2
\]

\[
\text{subject to}
\gamma' \left( \beta P_{2}^{m,l} g_{2,l}^2 + P_{n,m} S_{m,l}^2 + \sigma^2 + \sum_{j \in C_n \setminus I} \left( P_{j}^{m,l} g_{j,l}^2 \right) \right) \left( P_{2}^{m,l} g_{2,l}^2 \right) \leq 1, \quad \forall l \in C_n,
\]

\[
\gamma' \left( \beta P_{2}^{m,l} g_{2,l}^2 + P_{n,m} S_{m,l}^2 + \sigma^2 + \sum_{j \in C_n \setminus I} \left( P_{j}^{m,l} g_{j,l}^2 \right) \right) \leq 1, \quad \forall l \in C_n,
\]

\[
\gamma' \left( \beta P_{2}^{m,l} g_{2,l}^2 + P_{n,m} S_{m,l}^2 + \sigma^2 + \sum_{j \in C_n \setminus I} \left( P_{j}^{m,l} g_{j,l}^2 \right) \right) \leq 1, \quad \forall l \in C_n.
\]

where \( \gamma' = \gamma' / \ln (1 - O_{y})^{-1} \). We observe that the constraint (14b) is obtained by using the upper bound of the outage probability in (13) followed by basic mathematical manipulations. Similar to (14b), the constraint in (9c) is simplified to (14c) by exploiting the upper bound of the outage probability in (9c) followed by basic algebra. Also, the objective function is changed from maximization to minimization of the inverse, where \( x / y \) is equivalent to \( \min \gamma' \) for \( x, y > 0 \). Finally, each of the box constraints in (9d)-(9f) is replaced by two constraints that basically apply the same constraints to the transmission powers.

Towards a solution for this problem, we first note here that the numerator of the objective function in (14a) is a posynomial function of the powers \( P_{n,m}^{m,l} P_{1}^{m,l} \) and \( P_{2}^{m,l} \), where each term is posynomial and posynomials are closed on multiplication and addition [27]. Also, as the denominator is a monomial, the objective function is a posynomial, where the result of a posynomial divided by a monomial is posynomial function [27]. Moreover, we can readily observe that the inequalities in (14b)-(14c) are posynomial functions of the powers \( P_{n,m}^{m,l} P_{1}^{m,l} \) and \( P_{2}^{m,l} \), while the constraints in (14d)-(14f) are monomial functions. Hence, the problem in (14) is a GP in the variables \( P_{n,m}^{m,l} P_{1}^{m,l} \) and \( P_{2}^{m,l} \). An efficient global solution of the GP in (14) can be obtained by using the interior-point method for GPs as detailed in [27].

\[\text{B. CHANNEL ASSIGNMENT}\]

After finding the capacity \( R_{n,m} \) using (8) based on the optimal PA determined by the interior-point method for all possible combinations of the \( M \) V2I links and clusters, the RA problem in (7) can now be expressed as

\[
\max_{\{a_{n,m}\}} \sum_{n=1}^{N_{c}} \sum_{m=1}^{M} a_{n,m} R_{n,m}
\]

subject to

\[
\sum_{n=1}^{N_{c}} a_{n,m} \leq 1, \quad a_{n,m} \in \{0, 1\}, \quad \forall m \in M,
\]

\[
\sum_{m=1}^{M} a_{n,m} \leq 1, \quad a_{n,m} \in \{0, 1\}, \quad \forall n \in N_{C}.
\]
which is a maximum weight bipartite matching problem that can be efficiently solved by the Hungarian method [21]. In this problem, the weight matrix is \( R \), where \( R \in \mathbb{R}^{N_c \times N_c} \) and each entry \( R_{n,m} \) is given by (8). In the CA problem, each of the \( N_c \) clusters will be allowed to share one of the \( M \) V2I links’ RBs such that the sum of the capacities of the V2I links is maximized. To make the implementation of the proposed FD scheme straightforward, Algorithm 2 that shows the steps of the proposed scheme is presented.

**Algorithm 2 Proposed CA FD Algorithm**

1. Form the \( N_c \) clusters as described in Algorithm 1.
2. for \( n = 1 \) to \( N_c \) do
3. for \( m = 1 \) to \( M \) do
4. Find \( R_{n,m} \) that is given by (8) using the optimal PA obtained by solving (14) using the inner-point method.
5. end for
6. end for
7. Use the Hungarian method [21] to find the CA that maximizes the sum of the capacities of the V2I links.

As compared to the PA of the HD scheme in [1], the solution of the OP in (14) indeed has higher complexity. Accordingly, a second solution with lower complexity will be presented in the next subsection. The complexity of the proposed PA schemes and the PA of the HD scheme in [1] will be discussed and compared in Section VI-C. The GP-based solution is presented here due to its flexibility for modifications such as adding more constraints or modifying the objective function as long as the objective function and all inequalities can be formed as posynomial functions (note that equality constraints must be monomials). For instance, the total power expenditure constraint (i.e., \( P_{n,m,n} + \sum_{j \in C_n} (P_{1,j}^{m,j} + P_{2,j}^{m,j}) \leq P_{\text{max}}^n \)) can be added because it is a posynomial function. Also, including a minimum acceptable rate constraint for the V2I links is straightforward. More importantly, by slightly modifying this formulation, scenarios like maximizing the sum of the capacities of the V2I and V2V links or using FD communication in V2I links can be investigated, where the solution can serve as a perfect upper bound performance to other solutions that may use heuristic method or simplified assumptions but have lower complexity.

### C. ALTERNATIVE LOW-COMPLEXITY POWER ALLOCATION

Here, the PA problem in (9) will be solved with low computational complexity. Towards that end, the simplified expressions of the outage probabilities constraints (14b)-(14c) are exploited. The PA problem of the \( n \)-th V2I link and the \( n \)-th cluster that reuses the \( m \)-th RB can be expressed as

\[
\max_{(P_{n,m}^{1}, P_{n,m}^{2})} \sum_{l \in C_n} (P_{1,l}^{m,l} + P_{2,l}^{m,l}) + \sigma^2 \quad (16a)
\]

subject to

\[
\begin{align*}
\gamma'_l \left( \beta P_{1,l}^{m,l} g_{l,1}^{\text{SI},1} + P_{n,m} g_{m,l}^{c,1} + \sigma^2 + \sum_{j \in C_n} (P_{1,j}^{m,j} g_{j,l}^{1,1} + P_{2,j}^{m,j} g_{j,l}^{1,1}) \right) / P_{1,l}^{m,l} g_{l,1}^{1,1} + P_{2,l}^{m,l} g_{l,1}^{1,1} & \leq 1, \quad \forall l \in C_n, \quad (16b) \\
\gamma'_l \left( \beta P_{1,l}^{m,l} g_{l,1}^{\text{SI},1} + P_{n,m} g_{m,l}^{c,1} + \sigma^2 + \sum_{j \in C_n} (P_{1,j}^{m,j} g_{j,l}^{1,1} + P_{2,j}^{m,j} g_{j,l}^{1,1}) \right) / P_{1,l}^{m,l} g_{l,1}^{1,1} & \leq 1, \quad \forall l \in C_n, \quad (16c) \\
0 & < P_{n,m} \leq P_{\text{max}}^n, \quad (16d) \\
0 & < P_{l}^{m,l} \leq P_{\text{max}}^l, \quad \forall l \in C_n, \quad (16e) \\
0 & < P_{l}^{m,l} \leq P_{\text{max}}^l, \quad \forall l \in C_n. \quad (16f)
\end{align*}
\]

The optimal PA problem in (16) necessitates that the \( 2N_c \) outage constraints in (16b)-(16c) be met with equality. This can be proved by contradiction as follows. Let us assume that at the optimal point, there is at least one of the \( 2N_c \) outage constraints that do not satisfy the equality, i.e., for some \( l \), we have

\[
\gamma'_l \left( \beta P_{1,l}^{m,l} g_{l,1}^{\text{SI},1} + P_{n,m} g_{m,l}^{c,1} + \sigma^2 + \sum_{j \in C_n} (P_{1,j}^{m,j} g_{j,l}^{1,1} + P_{2,j}^{m,j} g_{j,l}^{1,1}) \right) / P_{1,l}^{m,l} g_{l,1}^{1,1} + P_{2,l}^{m,l} g_{l,1}^{1,1} < 1. \quad (17)
\]

This means, however, that we still can increase \( P_{n,m} \) and/or decrease \( P_{l}^{m,l} \) until equality is reached. Note that the objective function in (16a) is monotonically increasing with \( P_{n,m} \), while decreasing \( P_{l}^{m,l} \) helps in satisfying the other outage constraints and increases the objective function (i.e., less interference to the BS and other vehicles in the cluster). Therefore, the inequality in the outage constraints contradicts the optimality of the solution. Accordingly, at optimality, we have \( 2N_c \) equality constraints in which \( 2N_c + 1 \) variables need to be found. In particular, these variables are \( P_{c,n} \) and the \( 2N_{C_n} \) transmit powers of the \( N_{C_n} \) V2V pairs in the \( n \)-th cluster (\( P_{l}^{m,l} \) and \( P_{2,l}^{m,l} \) for \( l \in C_n \)). From the \( 2N_{C_n} \) equations, we can find the powers \( P_{1,l}^{m,l} \) and \( P_{2,l}^{m,l} \) for \( l \in C_n \) in terms of the power \( P_{c,n} \) as follows

\[
P_{v} = A^{-1}(P_{c,n}, \Psi_m + \sigma^2 \alpha), \quad (18)
\]

where \( A \in \mathbb{R}^{2N_c \times 2N_c} \) and \( P_v, \Psi_m \) and \( \alpha \in \mathbb{R}^{2N_c \times 1} \). These parameters are defined as

\[
P_v = \left( P_{1,1}^{m_1}, P_{1,2}^{m_1}, \ldots, P_{1,N_{C_n}}^{m_1}, P_{2,1}^{m_1}, \ldots, P_{2,N_{C_n}}^{m_1} \right)^T, \\
\Psi_m = \left( \gamma_1 g_{m,1}^{c,2}, \gamma_2 g_{m,2}^{c,2}, \ldots, \gamma_{N_{C_n}} g_{m,N_{C_n}}^{c,2}, \\
\gamma'_1 g_{m,1}^{c,1}, \gamma'_2 g_{m,2}^{c,1}, \ldots, \gamma'_{N_{C_n}} g_{m,N_{C_n}}^{c,1} \right)^T, \\
\alpha = (\gamma_1, \gamma_2, \ldots, \gamma_{N_{C_n}}, \gamma_1', \gamma_2', \ldots, \gamma'_{N_{C_n}})^T.
\]
The matrix $A$ is given by

$$A_{i,j} = \begin{cases} 
\frac{1}{2} s_{i,j}, & \text{if } i \leq N_{C_n} \text{ and } i = j \\
-\gamma_{i}^{1} s_{i,j}, & \text{else if } i \leq N_{C_n} \text{ and } j \leq N_{C_n} \\
-\gamma_{i}^{2} s_{i,j}, & \text{else if } i \leq N_{C_n} \text{ and } j = i + N_{C_n} \\
-\gamma_{j}^{1} s_{i,j}, & \text{else if } j \leq N_{C_n} \text{ and } j = i - N_{C_n} \\
-\gamma_{j}^{2} s_{i,j}, & \text{else if } j > N_{C_n} \text{ and } i = j \\
\frac{1}{2} s_{i,j} - N_{C_n} - l - N_{C_n}, & \text{else if } j > N_{C_n} \text{ and } j = i - N_{C_n} \\
\frac{1}{2} s_{i,j} - N_{C_n}, & \text{else if } j > N_{C_n} \text{ and } j = i + N_{C_n} \\
\frac{1}{2} s_{i,j} - l - N_{C_n}, & \text{else if } j > N_{C_n} 	ext{ and } j > N_{C_n}. 
\end{cases}$$

(19)

Each row of the matrix $A$ is formed based on one of the $2N_{C_n}$ outage constraints in (16).

After substituting for the V2V pairs transmit powers ($P_{m,i}^{1}$ and $P_{m,i}^{2}$, $\forall i \in C_n$) in the objective function (16a) with their values in terms of $P_{m}^{*}$ using (18), the objective function becomes monotonically increasing with $P_{m}^{*}$. Accordingly, taking into account the power constraints (16d)-(16f), the optimal PA solution of the problem in (16) can be obtained as

$$P_{m}^{*} = \min \left\{ P_{m}^{\text{max}} - \frac{\sigma^2 B_{i}\alpha}{B_{i}\Psi_{m}} \right\}_{i=1}^{2N_{C_n}},$$

(20)

and

$$P_{v}^{*} = A^{-1} \left( P_{v,m}^{*} \Psi_{m} + \sigma^2 \alpha \right),$$

(21)

where $B_{i}$ is the $i$-th row of the matrix $A^{-1}$ and $P_{v}^{*} = \left( P_{1,m}^{*}, P_{2,m}^{*}, \ldots, P_{m,n}^{*}, P_{m,n}^{*}, \ldots, P_{m,n}^{*} \right)^{T}$. The capacity $R_{n,m}$ given by (8) can now be found using these optimal transmit powers and the complete solution of the FD RA problem can be obtained straightforwardly following Algorithm 2 with the PA in step 4 obtained using (20) and (21) instead of using the interior-point method.

VI. FURTHER EXTENSIONS AND INSIGHTS

In this section, a hybrid FD/HD scheme that merges the proposed FD scheme with the HD scheme in [1] is introduced. Then, an alternative formulation of the optimization problem is introduced, which is based on the slow fading parameters of the links. Lastly, the complexity of the proposed schemes is discussed.

A. PROPOSED HYBRID RESOURCE ALLOCATION SCHEME

Undoubtedly, using FD communications in V2V links introduces more interference as compared to HD V2V links. On the other hand, FD V2V links can achieve a required transmission rate $R_{v}$ at a lower SINR than HD links (i.e., $\gamma_{\text{V2I}} < \gamma_{\text{HD}}$) where, using Shannon’s capacity, $\gamma_{\text{V2I}} = 2^{\frac{R_{v}}{W}} - 1$ while $\gamma_{\text{HD}} = 2^{\frac{R_{v}}{W}} - 1$. A lower SINR threshold $\gamma_{\text{V2I}}$ can be met with either lower transmit powers in the V2V links and/or the FD V2V links can tolerate more interfering power from the V2I link that uses the same RB. The capacity of a V2I link is monotonically decreasing with the transmission power used in the V2V links that reuse its RB. Accordingly, using FD communications in V2V links paves the way for V2I links to enjoy a higher capacity as will be clearly shown in Section VII. However, if $R_{v}$ for the V2V links is small, the difference between the FD and HD SINR thresholds will be small as well. Consequently, if the interference resulting from using FD communication has more negative impact on the system performance than the difference in the SINR thresholds, HD communication might actually offer better performance for the considered VCN. The fact that V2V pairs may serve various applications with different data rates (i.e., $R_{v}$ could be small or large) motivates us to introduce a heuristic hybrid RA scheme that offers better performance than the HD scheme in [1] for all potential data rates as will be shown in the sequel.

As there is no inter-cluster interference and the PA for each cluster is found independently, some clusters can work in FD mode while others can use HD mode if it offers higher capacity. Accordingly, for each combination that consists of a V2I link and a cluster that shares the same RB, we will find the capacity of the FD mode $R_{n,m}^{\text{FD, RA}}$ using (16a) and (16b) as well as the capacity in the HD mode $R_{n,m}^{\text{HD, RA}}$ using (16d)-(16f) and the mode that provides the higher capacity will be adopted for transmission. Hence, the capacity of the hybrid scheme can be found as $R_{n,m}^{\text{hybrid}} = \max \left( R_{n,m}^{\text{FD, RA}}, R_{n,m}^{\text{HD, RA}} \right)$. After finding the capacity $R_{n,m}^{\text{hybrid}}$ for all the possible combinations, the CA can now be found by the Hungarian method using $R_{n,m}^{\text{hybrid}}$ as the weight matrix instead of $R_{n,m}$ in step 7 of Algorithm 2.

B. PROPOSED SLOW-FADING BASED RESOURCE ALLOCATION SCHEME

As previously explained, the proposed FD and hybrid FD/HD schemes depend only on the large-scale fading and statistical information (viz., the expected values in (11)) of the small-scale fading of the V2V links as given in (20) and (21). Hence, as mentioned in Section III-B, since the BS only tracks the statistical information of the small-scale fading of the V2V links, it avoids the significant overhead of transmitting instantaneous CSI due to the high mobility of the vehicles. Although the proposed schemes reduce the reporting overhead from the V2V pairs to the BS, the BS must still inform each vehicle involved in V2V communications with the computed optimal PA and CA. Also, although this is true for the PA step, the CA step, on the other hand, still depends on the instantaneous CSI of the V2I links as shown in (15a). Consequently, to reduce the overhead further, we herein present an alternative slow-fading based RA scheme where the average SINRs, i.e., certainty equivalents (CEs), of the V2I links are going to be used instead of the instantaneous channel states. The use of average SINRs in order to maximize the rate or to minimize the power...
expenditure is common in the literature (please refer to [1], [12], [23], [26] and [28] for such examples).

Now, in the RA problem in (7), the capacity of the $m$-th V2I link, $R_{n,m}$, that is given by (8) will be replaced by the capacity based on the average SINR given by

$$R_{n,m} = \log_2 \left( 1 + \frac{P_{n,m} g_m}{\sum_{j=1}^{N_{C_n}} (p_{m,j}^{1,1} s_{m,j}^1 + p_{m,j}^{2,2} s_{m,j}^2) + \sigma^2} \right).$$

(22)

As earlier, the new RA problem can be solved in two steps; PA followed by CA. Although the objective function of the PA problem in (16) has now changed, the optimal PA can still be found using (20) and (21). The optimality requires that the $2N_{C_n}$ outage constraints in (16b)-(16c) be met with equality, which can be proved by contradiction as presented in Section V-C. On the other hand, in the CA, the new weight matrix $R$ should be used instead of $R$ where each entry in the matrix, $R_{n,m}$, is given by (22). Specifically, Algorithm 2 can still be used after modifying step 4 to find $R_{n,m}$ using the optimal PA given by (20) and (21). Also, in step 7, the Hungarian method is used but the weight matrix is changed to $R$ instead of $R$.

One important observation is due here; since the V2I links may experience instantaneous channel states that are worse than the considered average SINRs, transmission reliability of these links cannot be guaranteed. To ensure that, the outage probabilities of these links need to be kept below a small acceptable threshold $O_c$. To achieve that, the V2I links can adjust their certainty equivalent margins (CEMs) such that the outage probabilities are kept below $O_c$. The CEM of the $m$-th V2I link can be expressed as [26]

$$CE_{m} = \frac{CE_{m}}{\gamma_{th}} = \frac{P_{n,m} g_m}{\gamma_{th} \left( \sum_{j \in C_n} p_{m,j}^{1,1} s_{m,j}^1 + \sum_{j \in C_n} p_{m,j}^{2,2} s_{m,j}^2 + \sigma^2 \right)}.$$

(23)

where $CE_{m}$ is the CE (i.e., the average SINR) of the $m$-th V2I link, $\gamma_{th}$ is the SINR threshold required to achieve a certain rate $R_m$ that is equal to $\log_2(1 + \gamma_{th})$. A large CEM means using an SINR that is well above the minimum required for reception, which in turns leads to a small outage probability [23]. The upper and lower bounds of the outage probability in terms of the CEM are found in [26, Eq. (9)]. Replacing the outage probability with its upper bound ensures that the highest outage probability that may occur remains below the considered threshold $O_c$, which can be expressed as

$$1 - \exp \left( - \frac{1}{CE_{m}} \right) \leq O_c,$$

(24)

where the left side of (24) represents the upper bound of the outage probability in terms of the CEM [26]. After basic manipulations, we can write (24) as

$$CE_{m} \times \ln(1 - O_c) \geq \gamma_{th}^C,$$

(25)

which means that at the average SINR, i.e., $CE_{m}$, using any transmission rate smaller than or equal to $\log_2(1 + \gamma_{th})$ ensures that the highest outage probability that may occur remains below the acceptable threshold $O_c$. Demanding a high reliability, i.e., small $O_c$, results in a small $\gamma_{th}^C$, which, in turn, means a lower capacity for the V2I links as given in (25) and will be shown in Section VII.

C. COMPLEXITY ANALYSIS

An important metric for evaluating the efficiency of the proposed schemes is the computational complexity. To assess that, the complexity of the proposed schemes are compared with that of the HD scheme in [1]. The RA problem of the proposed schemes as well as that of the HD scheme in [1] consist of a PA stage followed by a CA one. In all these schemes, the CA problem is solved using the Hungarian method. The weight matrix is $C$, where $C \in \mathbb{R}^{N_{C_n} \times N_{C_n}}$ and the complexity has an order of $O(N_{C_n}^3)$.

The proposed low-complexity PA scheme consists of two steps. First, finding the optimal power $P_{m,n}^*$ using (20), which is the process of finding the minimum number among $2N_{C_n} + 1$ values. This has a complexity equal to $O(2N_{C_n} + 1)$ [29]. As additive and multiplicative constraints are neglected in the computation of the big-O notation, the complexity $O(2N_{C_n} + 1) = O(N_{C_n})$. The second step involves finding the optimal $P_c$ using (21), which is solving a system of $2N_{C_n}$ linear equations using the inverse matrix $A^{-1}$, which has a complexity of $O(N_{C_n}^3)$ [30]. Accordingly, the complexity of proposed low-complexity PA is $O(N_{C_n}^3 + N_{C_n}^3)$. On the other hand, the PA in [1] is found by solving (16) and (17) in [1], which has a complexity $O(N_{C_n}^3 + N_{C_n}^3)$. The complexity of the proposed hybrid PA scheme is thus equal to the sum of the complexities of the PAs of the proposed FD scheme and the HD scheme in [1], which is still in the order of $O(N_{C_n}^3 + N_{C_n}^3)$. To conclude, both of the proposed FD and hybrid PA schemes have slightly higher complexity than the HD scheme in [1], but all of them still have the same order of complexity.

Lastly, solving the GP in (14) using the interior-point method has a higher order of complexity given by $O((k + m)^{0.5}(mk^2 + k^3 + n^3))$ [31], where $n$ is the number of variables in the problem that is equal to $2N_{C_n} + 1 + (14)$, $m$ is the number of the inequality constraints that is equal to $6N_{C_n} + 2$ and $k$ is the maximum number of monomials in the inequality constraints, where a posynomial function is the sum of monomial functions. In each of the constraints (14b) and (14c), there are $2N_{C_n} + 1$ monomials, i.e., $k = 2N_{C_n} + 1$.

VII. SIMULATION RESULTS

In this section, the performance of the proposed RA schemes are assessed based on simulations of the system model described in Section III. The freeway scenario is considered, which is well detailed in [32] and the various simulation parameters are summarized in Table 1. The performance of
TABLE 2. Simulation settings for the freeway scenario.

| Parameter                      | Value                                      |
|--------------------------------|--------------------------------------------|
| Cell radius                    | 500 m                                      |
| Carrier frequency              | 2 GHz                                      |
| Vehicle antenna gain (height)  | 3 dBi (1.5 m)                              |
| BS antenna gain (height)       | 8 dBi (25 m)                               |
| Distance between the freeway and the BS | 35 m                                      |
| Freeway lanes                  | 6 lanes of 4 m width                       |
| Vehicle drop model             | Spatial Poisson process                    |
| Average inter-vehicle distance | 2.5 sec × the absolute speed of the vehicle $v = 70$ km/h |
| $P_{\text{max}}^{\text{V2V}}$ and $P_{\text{max}}^{\text{V2I}}$ | 23 dBm                                    |
| $\sigma^2$                     | -114 dBm                                   |
| Path-loss model of the V2V links | LOS in WINNER II B1 [33]                    |
| Path-loss model of the V2I links | $128.1 + 37.6 \log_{10} d$, where $d$ in km |
| Shadowing model of the V2V (V2I) links | Log-normal with standard deviation 3 dB (8 dB) |
| Small-scale fading             | Rayleigh                                    |

the proposed schemes, in terms of the sum of the V2I links capacities, are compared with that of the HD scheme in [1] in order to show the advantages of using FD over HD communications in VCNs. We note that equal outage constraints are assumed for all V2V pairs (i.e., $O_v = O_v, \forall j \in N$) in all results presented in this article.

First, simulations with $N = 30$, $M = 10$, a target normalized transmission rate $R_v = 3$ bps/Hz for all V2V pairs and $\beta = \{-90 \text{ dB}, -60 \text{ dB}\}$ were performed. As discussed in Section VI-A, FD V2V links can achieve a required transmission rate $R_v$ at a lower SINR than HD links. Hence, the SINR threshold $\gamma_v$ can be met with either lower transmit powers in the V2V links (i.e., $P_{m,j}^{1}$ and $P_{m,j}^{2}$) and/or the FD V2V links can tolerate more interfering power $P_{n,m}^c$ from the $m$-th V2I link that uses the same RB. As can be seen from (8), the capacity of a V2I link is monotonically increasing (decreasing) with $P_{n,m}^c$ ($P_{m,j}^{1}$ and $P_{m,j}^{2}$). This is evident in Fig. 2, where the proposed FD scheme offers higher sum of the V2I link capacities than the HD scheme in [1]. The figure also shows that the proposed hybrid scheme outperforms the proposed FD scheme and the HD scheme in [1] over all the range of the outage probability threshold $O_v$ in all the considered scenarios.

In addition, the impact of the SIC on the performance of the proposed FD and hybrid schemes is depicted in the figure. Clearly, higher SIC improves the SINRs of the V2V links and thus the SINR threshold $\gamma_v$ in (16b)-(16c) can be met with lower transmit powers $P_{m,j}^{1}$ and $P_{m,j}^{2}$ in the V2V links and/or higher transmit power $P_{n,m}^c$ in the interfering V2I links. From (8), as the capacity of the V2I link $R_{n,m}^c$ is monotonically increasing (decreasing) with $P_{n,m}^c$ ($P_{m,j}^{1}$ and $P_{m,j}^{2}$), a higher sum of the V2I links capacities is achieved when $\beta = -90$ dB than the case with $\beta = -60$ dB. As can also be seen in Fig. 2, when low SIC is used, the performance of the proposed FD scheme is degraded significantly to a level worse than the HD scheme over the low outage constraints region ($O_v < 10^{-2}$). Finally, Fig. 2 shows that the three schemes offer better performance at higher maximum allowed outage probabilities. This is because when a higher outage is allowed in the V2V links, lower transmit powers can be used in the V2V links and/or higher transmit power in the interfering V2I links. Accordingly, outage events occur but within the tolerable threshold and as mentioned earlier, the capacity of each V2I link increases.

To further support our argument that the proposed FD scheme offers higher sum of the V2I links capacities because of the spectral efficiency of FD V2V links (i.e., having lower SINR threshold), Fig. 3 shows the sum of the transmit powers $P_{n,m}^c$ used in the $M$ V2I links of the proposed FD scheme...
and the HD scheme in [1]. From the figure, it is clear that the proposed FD scheme uses higher powers in the V2I links. Also, Fig. 3 shows the ratio between the sum of the transmit powers used in the V2I links and the sum of the powers used in the V2V links. As obviously seen, the proposed FD scheme has a higher ratio due to the reasons mentioned above about having lower SINR threshold. Since the capacities of the V2I links are monotonically increasing with the transmit powers $P_{r,n}^c$ used in the V2I links and decreasing with the powers used in the V2V links (i.e., $P_{1}^{m,j}$ and $P_{2}^{m,j}$) as given in (8), the proposed FD scheme offers higher sum of the V2I links capacities as shown in Fig. 2.

Next, we investigate the impact of the number of V2V pairs on the system performance as shown in Fig. 4. Simulations with $M = 10$, $\beta = -90$ dB, a target transmission rate $R_v = 3$ bps/Hz for all V2V pairs are performed for different number of V2V pairs $N \in \{10, 20, 30\}$. As $N$ increases, the number of V2V pairs in each cluster increases too. Thus, a larger number of V2V pairs will share the same RB, which results in more intra-cluster interference that, in turn, decreases the SINRs of both the V2V pairs in the cluster as well as the V2I links. When the SINRs of the V2V pairs decrease, lower transmit powers $P_{r,n}^c$ and/or higher transmit powers $P_{1}^{m,j}$ and $P_{2}^{m,j}$ should be used to meet the SINR threshold. Accordingly, the sum of the V2I links capacities decreases as the number of V2V pairs increases in the three schemes as shown in the figure. For the case $N = 30$, the performances of the proposed FD and hybrid schemes were very close to each other, which indicates that the HD mode was better than the HD mode in the majority of the clusters.

Fig. 5 depicts the impact of the target transmission rate of the V2V pairs on the system performance. Simulations with $M = 10$, $N = 30$ and $\beta = -90$ dB are implemented with various values of $R_v = \{1, 2, 3\}$ bps/Hz. For the cases $R_v \in \{2, 3\}$, as compared to the HD scheme in [1], the proposed FD scheme offers higher sum of the V2I links capacities because of the higher spectral efficiency of FD communications in V2V links (i.e., having lower SINR threshold). On the other hand, for the case $R_v = 1$, although the HD scheme in [1] has higher SINR threshold, it offers better performance. This is because the negative impact of the higher interference between the V2V pairs in FD mode (since each V2V pair contributes two links) was higher than the positive impact of the spectral efficiency of the FD communications. This result reveals that for small $R_v$ (e.g., $R_v < 1$), using HD communications in V2V links offers better performance for the VCN under consideration. Also, this result acts as the main motivation for proposing the hybrid scheme that always ensures superior performance in all potential scenarios at the price of a higher computational complexity. However, it is worth noting here that the orders of the complexity of the three schemes are equal as we have discussed in Section VI-C, which makes the cost negligible as compared to the expected improvement in the system performance.

In the next set of results, we compare the performance of the proposed slow-fading based RA presented in Section VI-B with the corresponding HD scheme in [1, Algorithm 7]. These results are summarized in Fig. 6 where simulations with $M = 10$, $N = 30$, $\beta = -90$ dB and $R_v = 3$ bps/Hz are conducted. Clearly, the proposed scheme offers a higher sum of the V2I links capacities as shown in the figure. As discussed in Section VI-B, to ensure the communication reliability, the V2I links can adjust their transmission rates based on the average SINR (i.e., CE) in order to keep the outage probability below the acceptable threshold $O_c$. As given in (25), asking for high reliability (i.e., small $O_c$) results in small $\gamma_0^{v}$, which, in turn, leads to a lower capacity for the V2I links. As shown in Fig. 6, the sum of the V2I links capacities indeed decreases as the outage threshold $O_c$ decreases.
On another front, Fig. 7 shows the impact of the employed clustering technique on the system performance in terms of the sum of the V2I links capacities. As discussed in Section III-C, the proposed scheme uses Algorithm 1 that minimizes the intra-cluster interference for clusters formation. By minimizing the intra-cluster interference, the interference terms at the denominators of the outage constraints (16b)-(16c) are minimized. Accordingly, the V2V pairs can meet their outage constraints using less transmission powers or allow for higher interfering power from the V2I link that shares the RB with the cluster. Since the capacity of the V2I links increases (decreases) monotonically with $P_{m,n}$, $P_{11,m,1}$ and $P_{21,m,1}$ as given in (16), decreasing the intra-cluster interference through clustering improves the system performance. To assess the impact of the clustering in Algorithm 1, different clustering schemes are used for comparison. First, random clustering based on a uniform distribution is used. Second, we modified Algorithm 1 to form clusters with equal number of members. To achieve that, if the selected cluster in Step 6 is already full (i.e., has $N/M$ members), we select the cluster with the second minimum in Step 5. As shown in Fig. 7, our proposed clustering technique indeed led to the best performance among all considered approaches, which confirms its efficiency.

Lastly, Fig. 8 compares the performance of the proposed in-band FD scheme with another approach, which we refer to as the dual-band FD scenario, in which clustering is made based on V2V links rather than V2V pairs. Accordingly, the two links that belong to the same V2V pair might end up in different clusters. Towards that end, Algorithm 1 is modified where the mutual interference between the links now consists of two terms instead of eight terms in Step 5. More specifically, these two terms represent the interference from the transmitter of one V2V link to the receiver of the other and vice versa if the two links belong to different V2V pairs. On the other hand, if the two links belong to the same V2V pair, the two terms simply represent the SI at each vehicle of the V2V pair. Based on the results shown in the figure, the dual-band scenario offers a higher sum of the V2I links capacities only if the SIC is low (i.e., residual SI $\beta$ is large, equal to $-30$ dB, for example). In the same time, at very low SIC, the HD mode is found to offer better performance than both the proposed in-band and dual-band FD schemes. Finally, since in the proposed hybrid scheme each cluster selects between the HD and the two FD modes based on which mode offers higher capacity for the V2I link that shares the same RB as discussed in Section VI-A, the proposed hybrid scheme clearly still offers the highest sum of the V2I links capacities among all considered scenarios as illustrated in Fig. 8.

\footnote{We would like to thank Reviewer 1 for this interesting suggestion.}
VIII. CONCLUSION

We proposed an optimal RA scheme for FD VCNs. This scheme has been designed based on the CSI of the V2I links as well as the large-scale fading parameters and statistical parameters of the small-scale fading of the V2V links to avoid the overhead of reporting the fast varying CSIs from the V2V links to the BS. To meet the requirements of the V2I and V2V links, the sum of the V2I links capacities has been maximized while the reliability of the V2V links was ensured by adding outage probability constraints with small tolerable thresholds. The RA problem was solved in two steps by finding the optimal PA first, followed by the CA. Noting that the interference resulting in FD communications might degrade the performance in some situations, we also proposed a hybrid HD/FD scheme. It has been shown that the proposed FD scheme always outperforms the HD scheme except for the case where V2I links require low transmission rate, while the proposed hybrid one always offers higher performance.

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