MEETING DIFFERENT QOS REQUIREMENTS OF VEHICULAR NETWORKS: A D2D-BASED APPROACH

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ABSTRACT

The widely deployed cellular network, assisted with device-to-device (D2D) communications, can provide a promising solution to support efficient and reliable vehicular communications. In this paper, we identify differentiated requirements for different types of vehicular links, i.e., high capacity for vehicle-to-infrastructure (V2I) links and ultra reliability for vehicle-to-vehicle (V2V) links, and attempt to maximize the ergodic capacity of V2I connections while ensuring reliability guarantee for each V2V link. To account for fast channel variations caused by high mobility, we propose to perform spectrum sharing and power allocation based only on slowly varying large-scale fading information of wireless channels. A novel algorithm that yields optimal resource allocation and is robust to channel variations is proposed. Their desirable performance is confirmed by computer simulation.

Index Terms— Vehicular networks, device-to-device (D2D) communications, spectrum sharing, bipartite graph.

1. INTRODUCTION

Vehicular communications have gained attention recently due to its potential to improve road safety and traffic efficiency, as well as provide richer infotainment (information and entertainment) experience on wheels [1, 2]. Infotainment applications and traffic efficiency messages generally require frequent access to the Internet or remote servers for media streaming, content sharing, etc., involving considerable amount of data exchange, and hence are ideally supported by the high-capacity vehicle-to-infrastructure (V2I) links. Meanwhile, safety-critical information usually entails spreading safety related messages among surrounding vehicles either in a periodic or event triggered way. As such, it is naturally supported by the vehicle-to-vehicle (V2V) links, which impose strict reliability and timeliness requirements. The legacy IEEE 802.11p standard has been shown to be inefficient in enabling highly reliable and scalable vehicular networks, whereas the device-to-device (D2D) assisted cellular networks have gained more recent popularity in serving such purposes [1]. The widely deployed cellular networks provide native support for V2I connections while the localized V2V links lend themselves well to the D2D technology [3, 4].

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Conceivably, high mobility in a vehicular environment causes the wireless channels to rapidly change over time, rendering inapplicable traditional radio resource management (RRM) schemes for D2D communications under full channel state information (CSI) assumption. To alleviate this issue, in [3], latency and reliability requirements of V2V links have been transformed into optimization constraints with large-scale fading information only, and a heuristic algorithm has been developed accordingly. In [4], multiple resource blocks are allowed to be shared not only between cellular and D2D users but also among different D2D-capable vehicles. However, the above mentioned works have not considered V2I and V2V connectivity jointly and differentiated quality of service (QoS) requirements for V2I and V2V links have not been acknowledged. In this paper, we identify and incorporate such QoS differentiation into problem formulation and develop spectrum and power allocation algorithms only based on slow fading parameters to enable simultaneous V2I and V2V communications with reduced signaling overheads.

2. SYSTEM MODEL

Consider a D2D-enabled vehicular communications network, where there exist M vehicles requiring high-capacity V2I communications, denoted as CUEs (cellular users), and K pairs of vehicles doing local V2V data exchange in the form of D2D communications, denoted as DUEs (D2D users). We note that all vehicles are capable of doing both V2I and V2V connections simultaneously, implying that CUEs and DUEs might refer to the same vehicles equipped with multiple radios in this article. We assume that all communicating parties in this paper are equipped with a single antenna. Denote the CUE set as $\mathcal{M} = \{1, \cdots, M\}$ and the DUE set as $\mathcal{K} = \{1, \cdots, K\}$. To improve spectrum utilization efficiency, orthogonally allocated uplink spectrum of CUEs is reused by the DUEs since uplink resources are less intensively used and interference at the base station (BS) is more manageable.

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

$$h_{m,B} = g_{m,B}\beta_{m,B}AL_{m,B}^{-\gamma} \triangleq g_{m,B}\alpha_{m,B}, \tag{1}$$

where $g_{m,B}$ is the small-scale fast fading power component and assumed to be exponentially distributed with unit mean, A is the pathloss constant, $L_{m,B}$ is the distance between the mth CUE and the BS, γ is the decay exponent, and $\beta_{m,B}$ is a log-normal shadow fading random variable with a standard deviation σ_s. Channel h_k between the kth D2D pair, interfering channel $h_{k,B}$ from the kth DUE to the BS, and interfering channel $h_{m,k}$ from the mth CUE to the kth DUE are similarly defined. We assume that the large-scale fading components of the channel, i.e., the path loss and shadowing of all links, are known at the BS since they are usually dependent on the location of users and vary on a slow scale. Meanwhile, each realization of the fast fading is unavailable at the BS since it varies rapidly in a vehicular environment, whereas its statistical characterization is assumed to be known.

To this point, the received signal-to-interference-plus-noise-ratios (SINRs) at the BS for the mth CUE and at the kth DUE can be expressed as

$$\gamma_m^c = \frac{P_m^c h_{m,B}}{\sigma^2 + \sum\limits_{k\in\mathcal{K}} \rho_{m,k} P_k^d h_{k,B}}, \tag{2}$$

and

$$\gamma_k^d = \frac{P_k^d h_k}{\sigma^2 + \sum\limits_{m\in\mathcal{M}} \rho_{m,k} P_m^c h_{m,k}}, \tag{3}$$

respectively, where P_m^c and P_k^d denote transmit powers of the mth CUE and the kth DUE, respectively, σ^2 is the noise power, and $\rho_{m,k}$ is the spectrum allocation indicator with $\rho_{m,k} = 1$ implying the kth DUE reuses the spectrum of the mth CUE and $\rho_{m,k} = 0$ otherwise. The ergodic capacity of the mth CUE with the assumption of Gaussian inputs is then given by $C_m = \mathbb{E}\left[\log_2\left(1 + \gamma_m^c\right)\right]$, where the expectation is taken over the fast fading distribution.

Recognizing differentiated requirements for different types of links, i.e., large capacity for V2I connections and high reliability for V2V connections, we maximize the sum ergodic capacity of M CUEs while guaranteeing the minimum reliability for each DUE. In addition, we set a minimum capacity requirement for each CUE as well to provide a minimum guaranteed QoS for them. The ergodic capacity of CUEs is computed through the long-term average over the fast fading, which implies the codeword length spans several coherence periods over the time scale of slow fading. To this end, the proposed optimization problem is formulated as

$$\max_{\substack{\{\rho_{m,k}\} \\ \{P_m^c\},\{P_k^d\}}} \sum_{m\in\mathcal{M}} \mathbb{E}\left[\log_2\left(1 + \gamma_m^c\right)\right] \tag{4}$$

$$\text{s.t.}\quad \mathbb{E}\left[\log_2(1 + \gamma_m^c)\right] \geq r_0^c, \forall m \in \mathcal{M} \tag{4a}$$

$$\Pr\{\gamma_k^d \leq \gamma_0^d\} \leq p_0, \forall k \in \mathcal{K} \tag{4b}$$

$$\sum_{m\in\mathcal{M}} \rho_{m,k} \leq 1, \rho_{m,k} \in \{0, 1\}, \forall k \in \mathcal{K} \tag{4c}$$

$$\sum_{k\in\mathcal{K}} \rho_{m,k} \leq 1, \rho_{m,k} \in \{0, 1\}, \forall m \in \mathcal{M} \tag{4d}$$

$$0 \leq P_m^c \leq P_{\max}^c, \forall m \in \mathcal{M} \tag{4e}$$

$$0 \leq P_k^d \leq P_{\max}^d, \forall k \in \mathcal{K}, \tag{4f}$$

where $P_{\max}^c$ and $P_{\max}^d$ are the maximum transmit powers of the CUE and DUE, respectively, r_0^c is the minimum capacity requirement of the data rate intensive CUEs while γ_0^d is the minimum SINR needed by the DUEs to establish a reliable link. $\Pr\{\cdot\}$ evaluates the probability of the input. Constraints (4a) and (4b) represent the minimum capacity and reliability requirements for each CUE and DUE, respectively. (4c) and (4d) mathematically model our assumption that the spectrum of one CUE can only be shared with a single DUE and one DUE is only allowed to access the spectrum of a single CUE. (4e) and (4f) ensure that the transmit powers of CUEs and DUEs cannot exceed their maximum limit. The proposed optimization problem represents a novel formulation factoring in unique features of channel variations of vehicular communications as well as differentiated QoS requirements for V2I and V2V links. However, this is a highly nonlinear nonconvex optimization problem due to its combinatorial nature.

3. SPECTRUM AND POWER ALLOCATION DESIGN

In this section, we propose to approach the optimization problem in (4) in two steps inspired by [5]. First, we exploit the separability of power allocation and spectrum sharing pattern design by noting that interference exists only within each CUE-DUE pair as dictated by (4c) and (4d). Focusing on each pair of CUE-DUE, we study its optimal power allocation to maximize the CUE ergodic capacity with reliability guaranteed for the DUE. We then check the feasibility of each CUE-DUE pair against the minimum capacity requirement for the CUE, rule out infeasible pairs, and construct a bipartite graph to find the optimal spectrum sharing pattern between the sets of CUEs and DUEs using the Hungarian method [6].

3.1. Power Allocation for Single CUE-DUE Pairs

Given an arbitrary spectrum reuse pattern, e.g., the kth DUE sharing the band of the mth CUE, the power allocation problem for the single CUE-DUE pair is simplified into

$$\max_{P_m^c, P_k^d} \mathbb{E}\left[\log_2\left(1+\gamma_m^c\right)\right] \tag{5}$$

$$\text{s.t. } \Pr\{\gamma_k^d \leq \gamma_0^d\} \leq p_0 \tag{5a}$$

$$0 \leq P_m^c \leq P_{\max}^c \tag{5b}$$

$$0 \leq P_k^d \leq P_{\max}^d, \tag{5c}$$

where the minimum capacity constraint for the CUE is temporarily left out and would be accounted for in the next step.

We evaluate the reliability constraint for the kth DUE in the following lemma whose proof is left out due to page limit.

Lemma 1. *The reliability constraint for the kth DUE, i.e. (5a) in the proposed single pair power allocation problem in* (5)*, can be expressed as*

$$P_m^c \leq \frac{\alpha_k P_k^d}{\gamma_0^d \alpha_{m,k}} \left(\frac{e^{-\frac{\gamma_0^d \sigma^2}{P_k^d \alpha_k}}}{1-p_0} - 1 \right) \triangleq f\left(P_k^d\right). \tag{6}$$

With the closed-form expression for reliability constraint (5a) given in Lemma 1, we define $P_{d,\max}^c = f\left(P_{\max}^d\right)$ and $P_{c,\max}^d = f^{-1}\left(P_{\max}^c\right)$. Note that $P_{c,\max}^d$ can be obtained through bisection search over the function $f(\cdot)$, which is a monotonically increasing function in the range of interest. We now derive the optimal solution to (5) in the following theorem without providing proof details due to page limit.

Theorem 1. *The optimal power allocation solution to optimization problem* (5) *is given by*

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

and

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

3.2. Pair Matching for All Users

To this end, we have obtained the optimal power allocation for each CUE-DUE pair as given in Theorem 1. In the next step, we need to eliminate those CUE-DUE combinations that do not satisfy the minimum QoS requirement for the CUE, i.e., (4a), even when the optimal allocation scheme obtained from (7) is applied. The closed-form expression for the ergodic capacity of the mth CUE when sharing spectrum with the kth DUE, defined as $C_{m,k}\left(P_m^c, P_k^d\right) \triangleq \mathbb{E}\left[\log_2(1+\gamma_m^c)\right]$, is derived in the following lemma.

Lemma 2. *The ergodic capacity, $C_{m,k}\left(P_m^c, P_k^d\right)$, of the mth CUE when sharing spectrum with the kth DUE is given by*

$$\begin{aligned} & C_{m,k}\left(P_m^c, P_k^d\right) \\ =& \frac{a}{(a-b)\ln 2}\left[e^{\frac{1}{a}} E_1\left(\frac{1}{a}\right) - e^{\frac{1}{b}} E_1\left(\frac{1}{b}\right)\right], \end{aligned} \tag{8}$$

Table 1. Optimal Resource Allocation Algorithm for (4) in D2D-enabled Vehicular Communications

Algorithm 1 Optimal Resource Allocation Algorithm for (4)

for $m = 1 : M$ **do**
  for $k = 1 : K$ **do**
    Obtain the optimal power allocation $(P_m^{c^*}, P_k^{d^*})$ from (7) for the single CUE-DUE pair.
    Substitute $(P_m^{c^*}, P_k^{d^*})$ into (8) to obtain $C_{m,k}^*$.
    if $C_{m,k}^* < r_0^c$ **then**
      $C_{m,k}^* = -\infty$.
    end if
  end for
end for
Use the Hungarian method [6] to find the optimal reuse pattern $\{\rho_{m,k}^*\}$ based on $\{C_{m,k}^*\}$.
Return the optimal spectrum reuse pattern $\{\rho_{m,k}^*\}$ and power allocation $\{(P_m^{c^*}, P_k^{d^*})\}$.

where $a = \frac{P_m^c \alpha_{m,B}}{\sigma^2}$, $b = \frac{P_k^d \alpha_{k,B}}{\sigma^2}$, and $E_1(x) = \int_x^\infty \frac{e^{-t}}{t} dt$ is the exponential integral function of the first order.

Substituting the optimal power allocation (7) in (8) yields the maximum ergodic capacity achieved when the mth CUE shares its spectrum with the kth DUE, denoted as $C_{m,k}^*$. If it is less than r_0^c, then this combination cannot meet the minimum capacity requirement for the CUE. Therefore, such a CUE-DUE pair is not feasible and we set $C_{m,k}^* = -\infty$.

After evaluating all possible combinations of the CUE-DUE pairs, the resource allocation problem (4) reduces to

$$\max_{\{\rho_{m,k}\}} \sum_{m\in\mathcal{M}} \sum_{k\in\mathcal{K}} \rho_{m,k} C_{m,k}^* \tag{9}$$

$$\text{s.t. } \sum_{m\in\mathcal{M}} \rho_{m,k} \leq 1, \rho_{m,k} \in \{0,1\}, \forall k \in \mathcal{K} \tag{9a}$$

$$\sum_{k\in\mathcal{K}} \rho_{m,k} \leq 1, \rho_{m,k} \in \{0,1\}, \forall m \in \mathcal{M}, \tag{9b}$$

which turns out to be a maximum weight bipartite matching problem and can be efficiently solved by the Hungarian method in polynomial time [6].

From the above discussion, our algorithm to find the optimal solution to the resource allocation problem in (4) for D2D-enabled vehicular communications can be summarized in Table 1. The proposed scheme depends solely on the slowly varying large-scale channel parameters and only needs to be updated every few hundred milliseconds, thus significantly reducing the signaling overhead.

Table 2. Simulation Parameters [7, 8]

Parameter	Value
Carrier frequency	2 GHz
Bandwidth	10 MHz
Cell radius	500 m
BS antenna height	25 m
BS antenna gain	8 dBi
BS receiver noise figure	5 dB
Distance between BS and highway	35 m
Vehicle antenna height	1.5 m
Vehicle antenna gain	3 dBi
Vehicle receiver noise figure	9 dB
Vehicle density λ	45 veh/km
Minimum safety distance	15 m
Traffic headway model	Gaussian distribution
Minimum capacity of DUE r_0^c	0.5 bps/Hz
SINR threshold for DUE γ_0^d	5 dB
Reliability for DUE p_0	0.01
Number of DUEs K	10
Number of CUEs M	10
Maximum CUE transmit power P_{max}^c	17, 23 dBm
Maximum DUE transmit power P_{max}^d	17, 23 dBm
Noise power σ^2	-114 dBm

Table 3. Channel Models for V2I and V2V Links [7]

Parameter	V2I Link	V2V Link
Pathloss model	128.1 + 37.6$\log_{10} d$, d in km	LOS in WINNER + B1 [9]
Shadowing distribution	Log-normal	Log-normal
Shadowing std deviation	8 dB	3 dB
Fast fading	Rayleigh fading	Rayleigh fading

4. SIMULATION RESULTS

In this section, simulation results are presented to validate the proposed algorithm for D2D-enabled vehicular networks. We model a single lane out of a multi-lane highway that passes through a single cell where the BS is located at its center. We adopt the high density traffic headway model in [10] and assume Gaussian distribution for the distance headway between vehicles according to [11]. The M CUEs and K DUEs are randomly chosen among generated vehicles, where DUE pairs are always formed between neighboring vehicles and the CUEs are assumed to have equal shares of the total bandwidth. The major simulation parameters are listed in Table 2 and the channel models for V2I and V2V links are described in Table 3. Note that all parameters are set to the values specified in Tables 2 and 3 by default, whereas the settings in each figure take precedence wherever applicable.

Fig. 1 demonstrates the sum ergodic capacity of CUEs with an increasing vehicle density on the highway. From the figure, the sum CUE capacity increases as the vehicles become denser since higher vehicle density is more likely to reduce inter-vehicle distance and give rise to more reliable V2V links with higher received power. As such, stronger interference from CUEs can be tolerated given the transmit power constraints of DUEs, which then leads to more power being allocated to CUEs and increase their sum ergodic capacity.

Fig. 2 shows the sum ergodic capacity of CUEs with respect to increasing SINR threshold of DUEs. We observe that

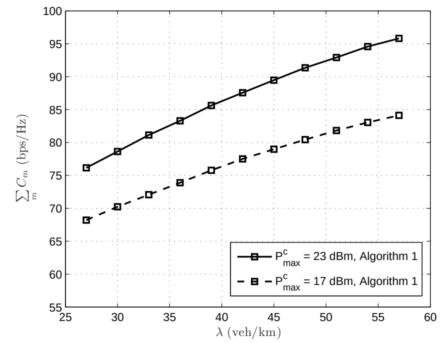

Fig. 1. Sum ergodic capacity of CUEs with varying vehicle density λ on the highway, assuming $P_{\text{max}}^d = P_{\text{max}}^c$.

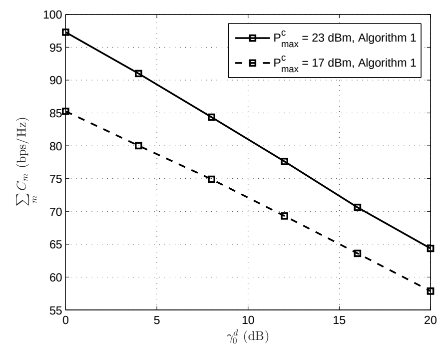

Fig. 2. Sum ergodic capacity of CUEs with varying DUE SINR threshold γ_0^d, assuming $P_{\text{max}}^d = P_{\text{max}}^c$.

the sum ergodic capacity will decrease when the minimum QoS requirement for DUEs grows large. Such performance degradation results from the reduced interference tolerability of DUEs due to an increase in their required SINR threshold, which will impose stricter constraints on the allowable transmit power of the pairing CUEs. Reduced transmit power of CUEs directly translates into a decrease of their sum ergodic capacity given all QoS constraints satisfied.

5. CONCLUSIONS

This paper investigates the spectrum sharing and power allocation design for D2D-enabled vehicular network. To address the challenge to track fast channel variations, we have taken into account the differentiated QoS requirements of vehicular communications and formulated optimization problems to design a resource allocation scheme based on slowly varying large-scale fading information only. A low-complexity algorithm has been proposed to maximize the sum ergodic capacity of V2I links while ensuring reliability for all V2V links and requiring low signaling overheads.

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