# Resource Allocation for Low-Latency Vehicular Communications with Delayed CSI Feedback

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*Abstract*- **Vehicular communications have stringent latency requirements on safety-critical information transmission. However, lack of instantaneous channel state information due to high mobility poses a great challenge to meet these requirements and the situation gets more complicated when packet retransmission is considered. Based on only the obtainable large-scale fading channel information, this paper performs spectrum and power allocation to maximize the ergodic capacity of vehicular-to infrastructure (V2I) links while guaranteeing the latency requirements of vehicular-to-vehicular (V2V) links. First, for each possible spectrum reusing pair of a V2I link and a V2V link, we obtain the closed-form expression of the packets' average sojourn time (the queueing time plus the service time) for the V2V link. Then, an optimal power allocation is derived for each possible spectrum reusing pair. Afterwards, we optimize the spectrum reusing pattern by addressing a polynomial time solvable bipartite matching problem. Numerical results show that the proposed queueing analysis is accurate in terms of the average packet sojourn time. Moreover, the developed resource allocation always guarantees the V2V links' requirements on latency.**

*Index terms*- **Vehicular communications, resource allocation, latency, queueing analysis, power allocation, spectrum allocation**

## 1. INTRODUCTION

The emergence of vehicle-to-everything (V2X) communications aims to make everyday vehicular operation safer, greener, and more efficient, thus paving the path to autonomous driving. The introduction of the fifth generation (5G) cellular system has enthusiastically made its potential to V2X communications part of its fanfare [2]–[5]. Various communications standards, e.g., dedicated short range communications (DSRC) [6] and the intelligent transportation system (ITS)-G5 [7], both based on the IEEE 802.11p standard, have been developed. However, recent studies [2], [4] have revealed several inherent issues of the 802.11p-based technologies, including scalability, potentially unbounded channel access delay, lack of quality-of-service (QoS) guarantees, and short-lived vehicle-to-infrastructure (V2I) connection. This is mainly because their physical and medium access control (MAC) layers have been originally designed for low mobility networks. To address these shortcomings, 3GPP has recently started projects towards supporting vehicle-to-everything (V2X) services in long term evolution (LTE) networks [4], [5], [8]. Widely deployed cellular networks, assisted with direct device-to-device (D2D) underlay communications [2], [9], have shown significant potential in enabling efficient and reliable vehicle-to-vehicle (V2V) and V2I communications, meeting the diverse V2X QoS requirements, and providing immunity to high mobility. Resource sharing requires a judicious allocation for mitigating interference and optimizing resource utilization for D2Dbased vehicular communications. Unlike traditional resource allocation designs, fast temporal channel variations due to high vehicle mobility pose a serious obstacle to the acquisition of high-quality channel state information (CSI). Along this line of thought, a heuristic location dependent uplink resource allocation scheme has been proposed in [10] for D2D terminals in vehicular networks, featuring spatial resource reuse with no explicit requirement on full CSI. A framework, consisting of vehicle grouping, reuse channel selection, and power control, has been developed in [11] to maximize the sum rate or minimally achievable rate of V2V links while restraining the aggregate interference to the uplink cellular transmission. In [12], a heuristic algorithm has been developed for the radio resource management in vehicular networks, which adapts to the large-scale fading of vehicular channels, i.e., path loss and shadowing that vary slowly. Similar system setups have been further considered in [13], where multiple resource blocks are shared not only between cellular and D2D users but also among different D2D-capable vehicles.

## 2. LITERATURE SURVEY

Recent development of autonomous driving and on-wheel infortainment services have accelerated the interest in vehicular communications. Vehicular communications include vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P) communications, which are collectively referred to as vehicle-to-everything (V2X) communications [1], [2 the V2V links have stringent demand on reliability and latency since the V2V links often exchange safety-critical information, such as common awareness messages (CAM) and decentralized notification messages (DENM) [3]. The IEEE 802.11p based vehicular communications have been widely studied in recent years. However, its carrier-sense based multiple access scheme faces great challenges in guaranteeing strict quality-of-service (QoS) requirements of V2X communications, especially when the traffic load grows heavy [4]. As an alternative, the cellular assisted vehicular communications with QoS-aware resource allocation have a sufficient potential to guarantee the diverse QoS requirements of different types of links, where the V2V and V2P communications are performed based on the cellularassisted device-to-device (D2D) technique [5]. The D2D technique enables proximate users to communicate directly with each other, which leads to the proximity, hop, and reuse gains [5]. To largely exploit these gains, most of the existing studies have preferred the reuse mode to the dedicated mode [6], where the reuse mode allows the D2D users to share the cellular users' spectrum and the dedicated mode assigns exclusive spectrum to the D2D users [7]. Traditional studies on D2D communications cannot be directly applied to vehicular communications due to the perfect channel state information (CSI) assumed available at the base stations (BS) or the D2D transmitters. This assumption does not hold any more since the channel varies fast owning to the high mobility of vehicles and it is quite difficult, if not impossible, to estimate and feed the instantaneous CSI back to the transmitters. To this end, the D2D-enabled vehicular communications should carefully address the challenge caused by the channel uncertainty.

## 3. SYSTEM MODEL

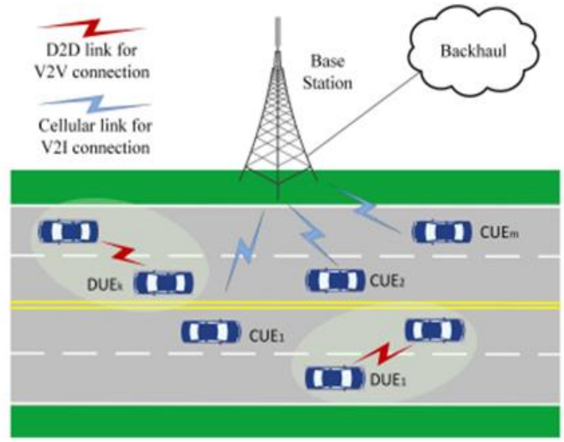


Fig. 1. D2D-enabled vehicular communications for both V2I and V2V links. In this paper, we propose to support both types of vehicular connections, i.e., V2I and V2V links, under the D2D-enabled cellular architecture where the V2I connectivity is enabled by macro cellular link and the V2V connectivity is supported through localized D2D link to achieve the dual benefits of D2D-enabled cellular networks. We base resource management on slow fading parameters and statistical information of the channel instead of instantaneous CSI to address the challenges caused by the inability to track fast changing wireless channels. Moreover, we identify and incorporate into problem formulation differentiated QoS requirements for V2I and V2V links in correspondence with their supported applications. That is, high link capacity is desired for V2I connections while safety-critical information of V2V connections places greater emphasis on link reliability. Sum and minimum ergodic capacities (long-term average over fast fading) of V2I links are maximized with a minimum QoS guarantee for V2I and V2V links, where the V2V link reliability is ensured by maintaining the outage probability of

received SINR below a small threshold. To the best of our knowledge, this is the first work that jointly considers the heterogeneous performance of V2I and V2V links and exploits only the large-scale fading information of the channels for resource allocation while taking a rigorous treatment of small-scale fading effects.

Consider a D2D-enabled vehicular communications network shown in Fig. 1, 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 vehicle 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 M = {1, • • • , M} and the DUE set as K = {1, • • • , 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 BS is more manageable. The channel power gain, hm,B, between CUE m and the BS is assumed to follow hm,B = gm,Bβm,BAL−γ m,B ∆= gm,Bαm,B, (1) where gm,B is the small-scale fast fading power component and assumed to be exponentially distributed with unit mean, A is the pathloss constant, Lm,B is the distance between the mth CUE and the BS, γ is the decay exponent, and βm,B is a log-normal shadow fading random variable with a standard deviation ξ. Channel hk between the kth D2D pair, interfering channel hk,B from the kth DUE to the BS, and interfering channel hm,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 locations of users and vary on a slow scale [9]. Such information can be estimated at the BS for links between CUEs/DUEs and BS, i.e., αm,B and αk,B, while for links between vehicles, i.e., αk and αm,k, the parameters will be measured at the DUE receiver and reported to the BS periodically. Meanwhile, each realization of the fast fading is unavailable at the BS since it varies rapidly in a vehicular environment with high mobility, whereas its statistical characterization is assumed to be known.

We develop a robust spectrum and power allocation scheme to improve the vehicular communications performance while taking into account the unique characteristics of D2D-enabled vehicular networks. 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 overheads than if directly applying traditional resource allocation schemes in vehicular networks. Recognizing QoS differentiation 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 reliability of DUEs is guaranteed through controlling the probability of outage events, where its received SINR γ d k is below a predetermined threshold γ d 0 . 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 [23]. It should be noted that how close the system performance can approach the ergodic capacity ultimately depends on the temporal variation of the vehicular channels as well as the tolerable delay. Faster variation induces more channel states within a given period, which makes the system performance approach the computed ergodic capacity quicker as the codeword needs to traverse most, if not all, channel states to average out the fading effects.

## 4. SIMULATION RESULTS

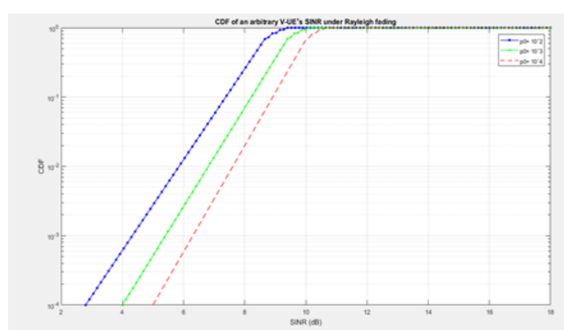

Fig.2. CDF of an arbitrary V-UE's SINR under Rayleigh fading

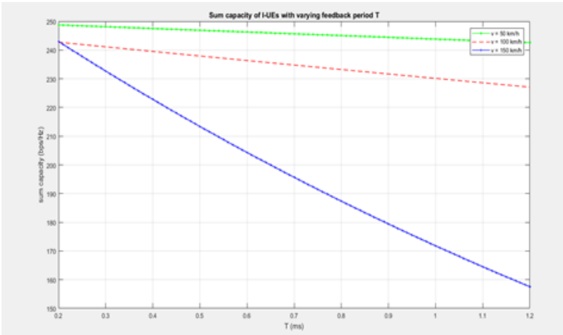


Fig. 3. Sum capacity of I-UEs with varying feedback period T

## 5. CONCLUSION

In this paper, we have investigated the spectrum sharing and power allocation design for D2D-enabled vehicular networks. Due to fast channel variations arising from high vehicle mobility, instantaneous CSI is hard to track in practice, rendering traditional resource allocation schemes for D2D-based cellular networks requiring full CSI inapplicable. To address this issue, we have taken into account the differentiated QoS requirements of vehicular communications and formulated optimization problems aiming to design a resource allocation scheme based on slowly varying large-scale fading information only. Robust algorithms have been proposed to maximize the sum and minimum ergodic capacity of V2I links, respectively while ensuring reliability for all V2V links. The current work is limited to allowing spectrum sharing within a single CUE-DUE pair while excluding more general spectrum reuse. Future works include relaxing such constraints and allowing multiple resource blocks to be shared by both V2I and V2V links, i.e., each resource block can be accessed by different V2I or V2V links and each vehicular link can exploit different resource blocks. The problem of optimal resource allocation will be studied accordingly.

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