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Linear Precoder Design with Imperfect CSI in Underlay Device-to-Device Communication for a Vehicular Platooning Scenario

Xin Zhang*, Andreas Festag†, Gerhard Fettweis*

*Vodafone Chair Mobile Communications Systems, Technische Universität Dresden, Germany
Email: {xin.zhang, gerhard.fettweis}@ifn.et.tu-dresden.de
†Fraunhofer Institute for Transportation and Infrastructure Systems (IVI), Germany
Email: andreas.festag@ivi.fraunhofer.de

***Abstract*—This paper proposes a novel design for linear precoder in underlay Device-to-Device (D2D) communication using cellular network, specifically for a use case with vehicle-to-vehicle communication and platooning. To increase the communication reliability, we develop an optimization algorithm for precoder that takes into account the outage probability when channel state information (CSI) is only partially available at devices and transmission could be in outage. The algorithm aims at maximizing the sum throughput over each transmission link received at one device, while constraining the interference caused by the transmit power from each device to the cellular network. Due to the intractable form of outage probability, an extended Markov Inequality is used to transform the problem into an upper-bound expression. A two-step alternating algorithm is then adapted to solve the multi-variable optimization. The proposed algorithm is compared with other state-of-the-art technologies in the field of vehicular communication for achieving high throughput. Simulation results show that our proposed algorithm outperforms the current techniques and achieves higher average throughput with extremely low outage probability, thus enables reliable vehicle-to-vehicle communication for platooning in a D2D underlay setting.**

Keywords*—D2D, Underlay Network, Outage Probability, Joint Optimization,

I. Introduction

With the advancement in 5G cellular systems, research efforts in Device-to-Device (D2D) communication have intensified. Originally proposed in the context of cellular relaying, D2D communication is regarded as an approach to offload a portion of data volume from the cellular network that enables a more efficient energy and spectrum management [1]. The performance benefits of D2D communication also unlock a wide range of applications, such as vehicle-to-vehicle (V2V) communication, which is considered as an important deployment scenario to improve road safety, traffic efficiency and driving comfort.

Currently, the state-of-the-art techniques for vehicular communication are primarily based on a WiFi variant, more precisely on the OCB mode.[1] This WiFi-based system enables immediate and direct communication among vehicles without the exchange of prior control information. However, without a fully de-centralized control as it is used in IEEE 802.11 OCB, the direct adhoc communication cannot be optimized for a given channel condition. For D2D communication in future 5G cellular systems, it is envisioned that D2D devices will share the radio resource with regular cellular users. With this vision, the benefits of adhoc networks and networks with centralized assistance can be combined. Devices will enjoy the capacity gain due to the sharing of spectrum resources between cellular and D2D users, user data rate gain due to the close proximity and potentially favorable propagation conditions for high data peaks rates, and lastly the latency gain when devices communicate over a direct link.

Two types of frequency spectrum sharing schemes exist in D2D communication – underlay and overlay. In the former, D2D users reuse resource blocks (RBs) of the time-frequency grid that are also available to cellular users. Both, D2D users and cellular users, have equal opportunity in accessing the radio resources. In the latter, D2D communication is carried out over dedicated RBs subtracted from cellular users [2]. In this paper, we assume D2D communication as an underlay network to cellular communication for its higher spectrum efficiency. In order to minimize the interference between cellular user and D2D devices, we assume that the available radio resources, which are shared between cellular users and devices, are in the uplink frequency spectrum because this approach causes less interference to a cellular user than using the downlink resource [3].

For vehicular networks, the direct communication between devices helps minimizing the latency by reducing the number of hops a packet traverses in conventional cellular network. For such systems, precoding represents a promising technique for interference management and hence to improve reliability and throughput. In this paper, we specifically consider platooning as one use case for vehicular communication due to its high market potential. In comparison to other use cases, platooning has more stringent requirements on communication reliability.

In previous work, [4] presented a solution to optimize the transmit power for D2D user and cellular user, so that the maximum throughput of a D2D link is reached with constraints on the QoS requirement of a cellular user. [5] optimizes the transmit power for the maximum sum-rate of both cellular and

[1] Outside the context of a Basic Service Set (BSS), formerly known as IEEE 802.11p and now integrated into the IEEE 802.11-2012 standard.

D2D users in underlay cellular networks and their respective constraints. Compared to the proposed method, the two reference methods focus on maximizing the throughput without considering outage probability. In [6], the cellular user's sum rate is optimized under the condition of satisfying vehicular users' requirement on latency and reliability. In this method, the outage probability of a particular vehicle is evaluated from its assigned radio resource block and the maximum allowable outage probability is limited as a constraint.

Outage probability is a measure of reliability for a network. Outage occurs when the actual throughput that can be supported by the channel is less than the actual assigned transmission rate; as a result, the transmission is in error. This mismatch can be the outcome of errors in channel estimation, feedback delay etc. Optimizing the throughput alone, and limiting the outage probability as in [6] would result in a tradeoff between throughput and outage. Hence, we present an approach that designs the precoding matrix from the aspect of outage. Instead of maximizing the sum throughput solely, we maximize the sum throughput of each transmission link received at a vehicle considering outage. For this purpose, the objective function targets at a joint optimization of the precoding matrix and the assigned transmission rate. The intractable form of outage probability is modeled using an extended Markov Inequality, which translates the expression of outage probability into an upper bound expression. Then an alternating algorithm is proposed to reach the sub-optimal solution. Throughout the paper, we assume that small scaled Multi-Input-Multi-Output (MIMO) antennas would be installed in D2D devices as it is considered in 5G network.

The remainder of this paper is organized as follows: Sec. II introduces the system model that takes into account the specific aspects of the platooning scenario and the corresponding channel model. This is followed by the problem formulation including an analysis of the relation between the outage probability and the assigned transmission rate in Sec. III. Sec. IV presents the optimization algorithm and discuss the multivariate alternating optimization approach. Sec. V provides numerical examples. Finally, Sec. VI draws conclusions.

II. System Model

A. System Scenario

We consider a single cell time division duplexed (TDD) system as illustrated in Fig. 1, where a segment of the freeway is covered. Vehicles on the freeway, that drive in a platoon, share a common mobility pattern and exchange data to improve road safety and capacity. The control of such formation can be fully decentralized (Cooperative Advanced Cruise Control, C-ACC) or centralized (platoon). In the latter case, one of the vehicles, typically the vehicle in front of the platoon, maintains platoon membership and coordinates inter- and intra-platoon maneuvers. It is common to both cases, the distributed and centralized, that each vehicle keeps a minimum distance to the vehicle in front, and maintain this distance during its stay in the platoon. For simplicity, we will refer to platoon for both cases in this paper.

All vehicles in a platoon communicate to each other freely, either in broadcast messages or in unicast messages or both, as illustrated in Fig. 1. Let $M' \triangleq 1, 2, \dots, M$ and

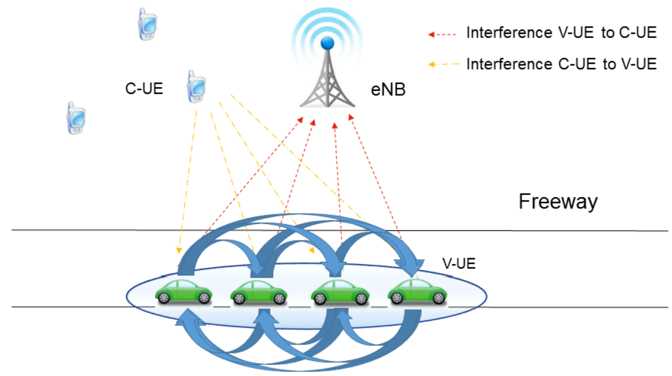


Fig. 1. Illustration of the considered D2D underlay communication system

$K' \triangleq 1, 2, \dots, K$ denote the set of cellular users (denoted as C-UEs) and the set of vehicles (denoted as V-UEs) in n-th cell respectively. A Base Station (BS) is located in the center of each cell with radius R and the shortest distance D to the highway. The channel state information (CSI) is estimated at each vehicle and fed back to BS periodically.

In this paper, we consider a communication scenario with only broadcast messages among vehicles. As a result, to any vehicle in the platoon, all messages from other vehicles are desirable, hence in this case the interference consists of receiver noise and interference from cellular user due to the sharing of radio resource. Fig. 2 illustrates the interference situation in this scenario. The blue dotted arrow denotes the cellular communication between C-UE and V-UE, the green arrow denotes the broadcast communication channel from all devices to device 1. The green arrow for channel $H_{1,1}$ is only for illustration purpose. In the channel model structure that we discuss in the next session, this portion is null.

Notation: The operator $\mathrm{dg}(\cdot)$ replaces each non-diagonal element of a matrix with zero, while $\mathrm{diag}(\cdot)$ places the elements of a vector on the diagonal of a matrix. Similarly, $\mathrm{blkdiag}(\cdot)$ puts matrices on the diagonal of a block diagonal matrix.

B. System Model

Assuming we have K vehicles forming a platoon, each k-th V-UE is equipped with b_k number of transceiver antennas. On an uplink radio resource, j-th V-UE transmits data $\mathbf{d}_j \in \mathbb{C}^{[b_j \times b_j]}$ to all other V-UE receivers from the same platoon. $\bar{\mathbf{d}}_{\bar{k}}$ denotes the data received at $\bar{k}$-th V-UE. The overall input data for all vehicles are denoted as $\mathbf{d} = [\mathbf{d}_1, \dots, \mathbf{d}_K]^T$. All elements of $\mathbf{d} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \mathbf{I})$ are assumed to be independent and identically distributed according to a complex Gaussian distribution with zero mean and unit variance.

Let $\mathbf{B} \in \mathbb{C}^{B_r \times B_t}$ denotes the overall precoding matrix where $B_t = B_r = \sum_{k=1}^{K} b_k$ denotes the total number of transceivers at the transmitting vehicle and the receiving vehicle respectively. It has an expression as follows

$$\mathbf{B} = [\mathbf{B}_1, ..., \mathbf{B}_K], \tag{1}$$

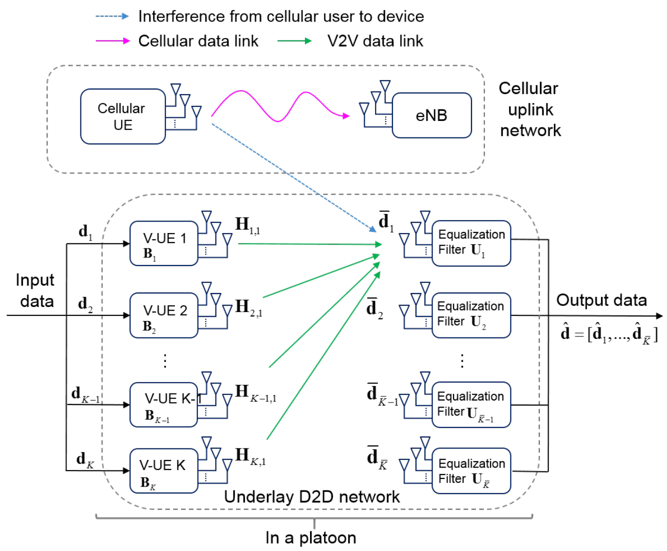


Fig. 2. System model of the considered D2D underlay communication

where each sub matrix $\mathbf{B}_j = [\mathbf{B}_{j,1}, \cdots, \mathbf{B}_{j,\bar{K}}]^T$ denotes the portion of the precoding matrix which resides on j-th transmitting V-UE. $\mathbf{B}_{\bar{k},j}$ denotes the portion of the precoding matrix which correspond to the path between j^{th} transmitting V-UE and $\bar{k}^{th}$ receiving V-UE.

At each V-UE, the received signal can be expressed as:

$$\bar{\mathbf{d}} = \mathbf{HBd} + \mathbf{n}, \tag{2}$$

where $\mathbf{H} \in \mathbb{C}^{[B_t \times B_r]} = [\mathbf{H}_1, ..., \mathbf{H}_K]^T$ corresponds to the broadcast channels among all V-UEs. Each submatrix $\mathbf{H}_j = [\mathbf{H}_{j,1}, \cdots, \mathbf{H}_{j,\bar{K}}]$ denotes broadcast channels between j-th transmitting vehicle to all other vehicles in the platoon and $\mathbf{n} = \left[\mathbf{n}_1^T, ..., \mathbf{n}_K^T\right]^T$ is the Gaussian noise. The received signals are then equalized by a linear filter $\mathbf{U}_{\bar{k}}$ at $\bar{k}$-th V-UE. The processed symbols after equalization are:

$$\hat{\mathbf{d}} = \mathbf{U}(\mathbf{HBd} + \mathbf{n}), \tag{3}$$

where the matrix $\mathbf{U} = \text{blkdiag}(\mathbf{U}_1, ..., \mathbf{U}_{\bar{K}})$ represents the combined received equalization filter.

C. Channel Model

In a platoon scenario where vehicles maintain a minimum distance to the preceding vehicle, the short inter-vehicle spacing guarantees a relatively static communication channel and a small fraction of multi-path reflections. Hence, we can assume the channel model among vehicles to be a block fading channel with single path reflection [7]. Following [8], we assume the channel model for cellular link is block fading channel as well.

Let the channel gain between j-th transmitting vehicle and $\bar{k}$-th receiving vehicle be $\lambda_{j,\bar{k}}$. $\hat{\mathbf{H}}_{j,\bar{k}}$ denotes the estimated channel matrix which follows a normal distribution with zero mean and $\lambda_{j,\bar{k}}$ variance, i.e $\hat{\mathbf{H}}_{j,\bar{k}} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \lambda_{j,\bar{k}}\mathbf{I})$.

In practice, CSI is often impaired by several factors, such as channel estimation errors, noisy pilot reception, or quantization error. The actual channel can be modeled by the summation of the estimated channel and channel error that are uncorrelated with each other. Assuming that the CSI is obtained by Minimum Mean Square Error (MMSE) estimation, the actual channel has the following relation:

$$\mathbf{H} = \hat{\mathbf{H}} + \mathbf{E}, \tag{4}$$

where the estimated channel matrix has an expression of

$$\hat{\mathbf{H}} = \begin{bmatrix} \mathbf{0} & \hat{\mathbf{H}}_{1,2} & \cdots & \hat{\mathbf{H}}_{1,\bar{K}} \\ \hat{\mathbf{H}}_{2,1} & \mathbf{0} & \cdots & \hat{\mathbf{H}}_{2,\bar{K}} \\ \vdots & & \ddots & \vdots \\ \hat{\mathbf{H}}_{K,1} & \cdots & & \mathbf{0} \end{bmatrix} \tag{5}$$

and the Gaussian error matrix

$$\mathbf{E} = \begin{bmatrix} \mathbf{0} & \mathbf{E}_{1,2} & \cdots & \mathbf{E}_{1,\bar{K}} \\ \mathbf{E}_{2,1} & \mathbf{0} & \cdots & \mathbf{E}_{2,\bar{K}} \\ \vdots & & \ddots & \vdots \\ \mathbf{E}_{\bar{K},1} & \cdots & & \mathbf{0} \end{bmatrix} \tag{6}$$

with $\mathbf{E}_{j,\bar{k}} \sim \mathcal{N}_{\mathbb{C}}(\mathbf{0}, \epsilon_{j,\bar{k}}\mathbf{I})$.

In our study, we assume the error variance $\epsilon_{j,\bar{k}}$ of any given V-UE to V-UE link is potentially different from the other links due to independent mean channel gains $\lambda_{j,\bar{k}}$.

III. Problem Formulation

Device-to-device communication is expected to enable a broad range of applications. In the domain of vehicle-to-vehicle communication, it has a great potential to enhance safety and traffic efficiency. Considering the increasing level of vehicle automation, communication can complement the vehicle's on-board sensors, support cooperative perception of vehicles and coordinate driving maneuvers among vehicles. For such scenarios, communication reliability is of utmost importance.

In a block fading channel, when the actual throughput that the channel can support is less than the assigned transmission rate, outage occurs. The probability of outage occurrence reduces the system reliability. To improve the overall reliability, we formulate the following optimization problem:

$$\begin{aligned} [\mathbf{B}^\star, \hat{\mathbf{\Gamma}}^\star] = \quad & \arg\max_{\mathbf{B}, \hat{\mathbf{\Gamma}}} \quad \textstyle\sum_{\bar{k}=1}^{K} \sum_{j=1}^{K} (1 - p_{\text{out},j\bar{k}}) \hat{\Gamma}_{j,\bar{k}}\,, \\ & \text{s.t.} \quad \text{tr}(\mathbf{B}_j \mathbf{B}_j^H) \leq \delta \quad \forall j, \end{aligned} \tag{7}$$

where $p_{\text{out},j\bar{k}}$ denotes the outage probability between j-th transmitting vehicle and $\bar{k}$-th receiving vehicle, i.e, $p_{\text{out},j\bar{k}} = \mathbb{P}\{\Gamma_{j,\bar{k}} < \hat{\Gamma}_{j,\bar{k}}\}$, $\hat{\Gamma}_{j,\bar{k}}$ the assigned transmission rate for the transmission link between j-th transmitting vehicle and $\bar{k}$-th receiving vehicle, while $\Gamma_{j,\bar{k}}$ is the instantaneous transmission rate between j-th transmitting vehicle and $\bar{k}$-th receiving vehicle and has the following expression:

$$\Gamma_{j,\bar{k}} = \log\det(\mathbf{I} + \mathbf{H}_{j,\bar{k}} \bar{\mathbf{B}}_{j,\bar{k}} \bar{\mathbf{B}}_{j,\bar{k}}^H \mathbf{H}_{j,\bar{k}}^H \mathbf{C}_k^{-1})\,, \tag{8}$$

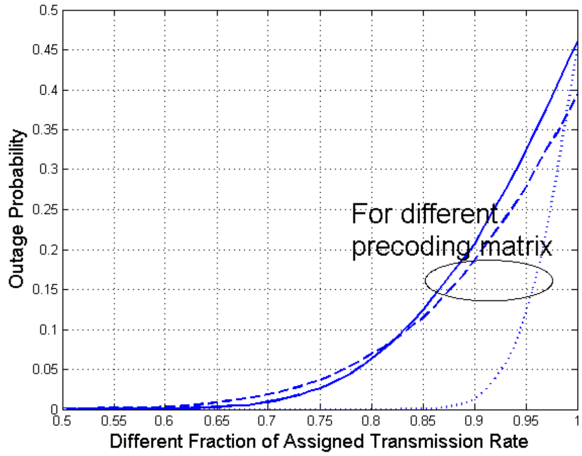


Fig. 3. Outage probability for each instance of precoding matrix against different assigned transmission rate

where $\mathbf{H}_{j,\bar{k}}\bar{\mathbf{B}}_{j,\bar{k}}\bar{\mathbf{B}}_{j,\bar{k}}^H\mathbf{H}_{j,\bar{k}}^H$ refers to the meaningful signal received at user k, while $\mathbf{C}_k$ indicates noise and interference to this user. $\mathbf{B}^\star$ and $\hat{\mathbf{\Gamma}}^\star = [\hat{\mathbf{\Gamma}}_1^\star, \cdots, \hat{\mathbf{\Gamma}}_K^\star]^T$ denote the optimized precoding matrix and the optimized assigned transmission rates for all V-UEs. δ is the maximum allowable transmit power set by regulation and system standardization.

Considering that outage may occur, the objective function aims at maximizing the sum throughput for each transmission link between vehicles, while constraining the transmit power of each vehicle to limit the interference to cellular users. The function jointly optimizes the precoding matrix and the assigned transmission rate.

The optimization problem implies several challenges. First of all, the closed form expression of the outage probability is not known if the precoding matrix is not fixed. Secondly, outage probability is a function of the precoding matrix and the assigned transmission rate, which are the variables to be optimized. As a result, the optimization problem is formulated with an optimizing variable and a variable, which is a function of both to-be-optimized variables. Fig. 3 shows the behavior of outage probability against different fractions of the assigned transmission rate. The assigned transmission rate is computed based on the estimated channel matrix. As illustrated in the figure, the outage probability increases with the assigned transmission rate, though not linearly. The outage probability also differs for each instance of the precoding matrix.

In order to solve the intractable expression of outage probability, the extension of Markov Inequality is applied [9]. It is stated that the following relation holds

$$\mathbb{P}\{x \geq a\} = \mathbb{P}\{f(x) \geq f(a)\} \leq \mathbb{E}\{f(x)\}/f(a) \quad (9)$$

for a strictly increasing and non-negative function $f(x)$. Substituting (9) into the definition of outage probability, we have

$$\mathbb{P}\{\Gamma_{j,\bar{k}} < \hat{\Gamma}_{j,\bar{k}}\} = 1-\mathbb{P}\{\Gamma_{j,\bar{k}} \geq \hat{\Gamma}_{j,\bar{k}}\} \geq 1-\mathbb{E}\{f(\Gamma_{j,\bar{k}})\}/f(\hat{\Gamma}_{j,\bar{k}}) \quad (10)$$

where $\Gamma_{j,\bar{k}}$ is the actual throughput that the channel can support.

With this relation, substituting (10) into the objective function, the latter is transformed into

$$[\mathbf{B}^\star, \hat{\mathbf{\Gamma}}^\star] = \arg\max_{\mathbf{B},\hat{\mathbf{\Gamma}}} \sum_{\bar{k}=1}^K \sum_{j=1}^K -\hat{\Gamma}_{j,\bar{k}} \frac{\mathbb{E}[f(\Gamma_{j,\bar{k}})]}{f(\hat{\Gamma}_{j,\bar{k}})}, \quad \text{s.t.} \quad \text{tr}(\mathbf{B}_j\mathbf{B}_j^H) \leq \delta \quad \forall j. \quad (11)$$

Let $f(x) = a + bx$, with $a, b \in \mathbb{R}_0^+$, the above objective function can be further reduced to

$$[\mathbf{B}^\star, \hat{\mathbf{\Gamma}}^\star] = \arg\max_{\mathbf{B},\hat{\mathbf{\Gamma}}} \sum_{\bar{k}=1}^K \sum_{j=1}^K -\nu_{j,\bar{k}}\mathbb{E}[\Gamma_{j,\bar{k}}], \quad \text{s.t.} \quad \text{tr}(\mathbf{B}_j\mathbf{B}_j^H) \leq \delta \quad \forall j \quad (12)$$

with

$$\nu_{j,\bar{k}} = b \cdot \hat{\Gamma}_{j,\bar{k}}/(a + b \cdot \hat{\Gamma}_{j,\bar{k}}) \quad (13)$$

where a and b are arbitrary constants. Study in [8] shows that the values of a and b have no significant impact on the overall performance due to the strictness of the extended Markov inequality.

Let $\mathbf{M}_{j,\bar{k}}^{MSE}$ denote the MSE matrix between j-th transmitting vehicle and $\bar{k}$-th receiving vehicle given that MMSE-receive filter is applied, i.e.,

$$\mathbf{M}_{j,\bar{k}}^{MSE} = \mathbb{E}[(\mathbf{d}_j - \mathbf{U}_{\bar{k}}^{MMSE}\bar{\mathbf{d}}_{\bar{k}_j})(\mathbf{d}_j - \mathbf{U}_{\bar{k}}^{MMSE}\bar{\mathbf{d}}_{\bar{k}_j})^H] \quad (14)$$

where $\mathbf{U}_{\bar{k}}^{MMSE}$ is the MMSE receive filter at $\bar{k}$-th receiving vehicle, $\bar{\mathbf{d}}_{\bar{k}_j}$ denotes the portion of message received at $\bar{k}$-th vehicle from j-th transmitting vehicle.

As proven in [10], the achievable rate for the transmission link between j-th transmitting vehicle and $\bar{k}$-th receiving vehicle holds as follows,

$$\Gamma_{j,\bar{k}} = -\log\det(\mathbf{M}_{j,\bar{k}}^{MSE}). \quad (15)$$

By Jensen's inequality [11], the expected achievable rate at $\bar{k}$-th vehicle is lower bounded by

$$\mathbb{E}\{\Gamma_{j,\bar{k}}\} = \mathbb{E}\{-\log\det\mathbf{M}_{j,\bar{k}}^{MSE}\} \geq -\log\det\mathbb{E}\{\mathbf{M}_{j,\bar{k}}^{MSE}\} = \tilde{\Gamma}_{j,\bar{k}}. \quad (16)$$

The objective function in (12) is now transformed into the following form,

$$[\mathbf{B}^\star, \hat{\mathbf{\Gamma}}^\star] = \arg\max_{\mathbf{B},\hat{\mathbf{\Gamma}}} \sum_{\bar{k}=1}^K \sum_{j=1}^K -\nu_{j,\bar{k}}\tilde{\Gamma}_{j,\bar{k}}, \quad \text{s.t.} \quad \text{tr}(\mathbf{B}_j\mathbf{B}_j^H) \leq \delta \quad \forall j. \quad (17)$$

IV. Optimization Algorithm

The optimization problem in (17) is a multi-variable optimization function with the form of Weighted Sum Rate (WSR) problem. As discussed in [12], a solution of this WSR problem can be found by alternatingly optimizing the MMSE filter matrix $\mathbf{U}$ and the precoding matrix $\mathbf{B}$ in an iterative manner.

A 2-step alternating algorithm to solving the objective function in (17) is proposed. In the first step, we obtain the optimal assigned transmission rate $\hat{\mathbf{\Gamma}}^\star$ by fixing the precoding

Algorithm 1 Proposed 2-step alternating algorithm

Input: $\hat{\mathbf{H}}$, σ_n^2, P_c, P_d, $\boldsymbol{\epsilon}$
Output: $\mathbf{B}$, $\hat{\boldsymbol{\Gamma}}$
Iteration index $i \leftarrow 0$
Init: $\mathbf{B}^i$=$\mathbf{B}^{\text{init}}$ according to [12], $\nu_{j,\bar{k}} = 1, \forall j, \bar{k}$
repeat
  Update $i = i + 1$
  (a) Compute the optimized transmission rate $\hat{\Gamma}^\star_{j,\bar{k}}, \forall j, \bar{k}$ by solving (19)
  (b) Update weights $\nu_{j,\bar{k}}, \forall j, \bar{k}$ with (13)
  (c) Calculate $\mathbf{B}^i$ with updated $\nu_{j,\bar{k}}$
until convergence

matrix $\mathbf{B}$. In the second step, we iteratively compute the precoding matrix $\mathbf{B}$ with the MMSE filter matrix $\mathbf{U}$ using the optimal transmission rate $\hat{\Gamma}^\star$. After all variables have been updated, a new iteration is executed. The whole process continues until the overall metric converges to a fixed point. It is known that with alternating optimization a local optimum can be obtained, while global optimality cannot be guaranteed unless the function subject to optimization is smooth and convex [13]. The procedures of the proposed algorithm is shown in the following.

1) Step 1: In order to obtain the optimal assigned transmission rate, we fix the precoding matrix. At the very first step, we obtain the initial precoding matrix $\mathbf{B}$ by assuming the outage probability to be zero and imperfect CSI. The objective function for calculating the initial precoding matrix is

$$\begin{aligned} [\mathbf{B}^\star] = \quad & \arg\max_{\mathbf{B},\mathbf{U}} \quad \textstyle\sum_{\bar{k}=1}^{K} \sum_{j=1}^{K} \Gamma_{j,\bar{k}} \,, \\ & \text{s.t.} \quad \text{tr}(\mathbf{B}_j \mathbf{B}_j^H) < \gamma_m \quad \forall m. \end{aligned} \tag{18}$$

Note that $\Gamma_{j,\bar{k}}$ in (18) refers to the actual throughput supported by the channel. A solution for solving this objective function under imperfect CSI was presented in [12]. With the initial precoding matrix, we optimize the transmission rate for a given channel estimate. The objective function can then be written as

$$\begin{aligned} \hat{\boldsymbol{\Gamma}}^\star = \quad & \arg\max_{\hat{\boldsymbol{\Gamma}}} \quad \textstyle\sum_{\bar{k}=1}^{K} \sum_{j=1}^{K} (1 - \mathbb{P}\{\Gamma_{j,\bar{k}}(\mathbf{B}) < \hat{\Gamma}_{j,\bar{k}}\}) \hat{\Gamma}_{j,\bar{k}} \,, \\ & \text{s.t.} \quad \hat{\Gamma}_{j,\bar{k}} \geq 0 \quad \forall k. \end{aligned} \tag{19}$$

The transmission rate $\hat{\Gamma}_{j,\bar{k}}$ in (19) is obtained by substituting the imperfect channel matrix in (4) in the following equation:

$$\hat{\Gamma}_{j,\bar{k}} = \log_2 \text{det}(\mathbf{I} + \tau_{j,\bar{k}} (\sigma_n^2 \mathbf{I} + \varphi_c)^{-1}) \tag{20}$$

where $\tau_{j,\bar{k}} = \mathbf{H}_{j,\bar{k}} \mathbf{B}_{\bar{k},j} \mathbf{B}_{\bar{k},j}^H \mathbf{H}_{j,\bar{k}}^H$ refers to the desired signal received between j-th transmitting vehicle and $\bar{k}$-th receiving vehicle. While $\varphi_c = \lambda_c P_c$ indicates cellular interference to the receiving vehicle, λ_c is the cellular channel gain compliant with LTE requirement and P_c is the maximal allowable transmit power from cellular user. Outage probability $\mathbb{P}\{\Gamma_{j,\bar{k}}(\mathbf{B}) < \hat{\Gamma}_{j,\bar{k}}\}$ is generated with respect to error $\mathbf{E}$ using Monte-Carlo simulations for each precoding matrix $\mathbf{B}$. $\hat{\Gamma}^\star_{j,\bar{k}}$ is obtained when (19) gives the maximum value.

2) Step 2: With $\hat{\Gamma}^\star_{j,\bar{k}}$ obtained in the first step, $\nu_{j,\bar{k}}$ in (17) can be updated according to (13). To solve (17), we first derive $\mathbb{E}(\mathbf{M}_{j,\bar{k}})$ with the imperfect CSI in (4).

$$\begin{aligned} \bar{\mathbf{M}}_{j,\bar{k}} &= \mathbb{E}\{\mathbf{M}_{j,\bar{k}}\} \\ &= \mathbf{I} + \mathbf{U}_{\bar{k}} (\hat{\mathbf{H}}_{j,\bar{k}} \mathbf{B}_{\bar{k},j} \mathbf{B}_{\bar{k},j}^H \hat{\mathbf{H}}_{j,\bar{k}}^H + \sigma_n^2 \mathbf{I}) \mathbf{U}_{\bar{k}}^H \\ &\quad + \zeta_{j,\bar{k}} \mathbf{U}_{\bar{k}} \mathbf{U}_{\bar{k}}^H - \mathbf{U}_{\bar{k}} \hat{\mathbf{H}}_{j,\bar{k}} \bar{\mathbf{B}}_{\bar{k},j} - \bar{\mathbf{B}}_{\bar{k},j}^H \hat{\mathbf{H}}_{j,\bar{k}}^H \mathbf{U}_{\bar{k}}^H \end{aligned} \tag{21}$$

where $\zeta_{j,\bar{k}} = \epsilon_{j,\bar{k}} \cdot \mathbf{1}_{1 \times b_{\bar{k}}} \cdot \text{diag}(\mathbf{B}_{\bar{k},j} \mathbf{B}_{\bar{k},j}^H)$.

The diagonal elements in $\bar{\mathbf{M}}_{j,\bar{k}}$ refer to the error variances of the data streams between antennas. The sum MSE for each transmission link between j-th transmitting vehicle and $\bar{k}$-th receiving vehicle is expressed as $\varsigma_{j,\bar{k}} = tr(\bar{\mathbf{M}}_{j,\bar{k}})$.

By setting the derivative of $\varsigma_{j,\bar{k}}$ with respect to $\mathbf{U}_{\bar{k}}$ to be zero, we obtain the expression of MMSE filter at $\bar{k}$-th receiving vehicle as follows:

$$\mathbf{U}_{\bar{k}}^{\text{MMSE}} = \mathbf{B}_{\bar{k},j}^H \hat{\mathbf{H}}_{j,\bar{k}}^H (\hat{\mathbf{H}}_{j,\bar{k}} \mathbf{B}_{\bar{k},j} \mathbf{B}_{\bar{k},j}^H \hat{\mathbf{H}}_{j,\bar{k}}^H + (\sigma_{n,k}^2 + \zeta_{j,\bar{k}}) \mathbf{I})^{-1}. \tag{22}$$

The expected value of the MSE matrix, $\bar{\mathbf{M}}_{j,\bar{k}}^{MSE}$, can then be obtained by substituting (22) into (21).

It was shown in [10] and [12] that the WSR maximization problem of the form in (17) is equivalent to a Weighted-sum MMSE (WMMSE) minimization problem, if the weighting matrices $\mathbf{W}_{j,\bar{k}} = \nu_{j,\bar{k}} (\bar{\mathbf{M}}_{j,\bar{k}}^{MSE})^{-1}$, such that

$$\begin{aligned} \mathbf{B}^\star = \quad & \arg\max_{\mathbf{B}} \quad \textstyle\sum_{\bar{k}=1}^{K} \sum_{j=1}^{K} \text{tr}(\mathbf{W}_{j,\bar{k}} \bar{\mathbf{M}}_{j,\bar{k}}^{MSE}) \\ & \text{s.t.} \quad \text{tr}(\mathbf{B}_j \mathbf{B}_j^H) < \gamma_j \quad \forall j, \end{aligned} \tag{23}$$

where

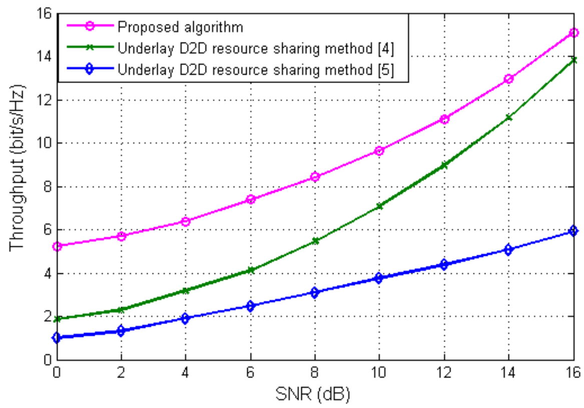
$$\bar{\mathbf{M}}_{j,\bar{k}}^{\text{MSE}} = (\mathbf{I} + \mathbf{B}_{\bar{k},j}^H \hat{\mathbf{H}}_{j,\bar{k}}^H \bar{\mathbf{C}}_{j,\bar{k}}^{-1} \hat{\mathbf{H}}_{j,\bar{k}} \mathbf{B}_{\bar{k},j})^{-1}, \tag{24}$$

$$\bar{\mathbf{C}}_{j,\bar{k}} = (\sigma_n^2 + \zeta_{j,\bar{k}}) \mathbf{I} + \varphi_c. \tag{25}$$

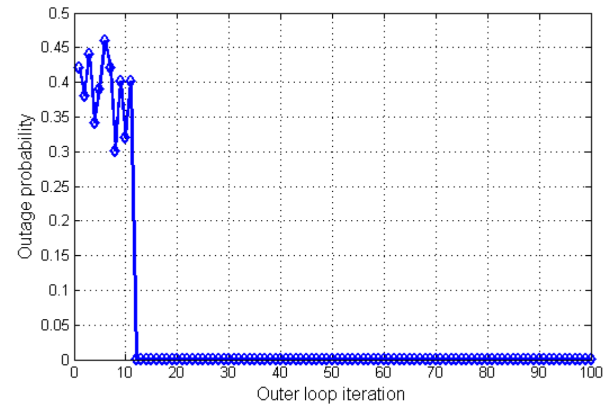
A solution for the optimization problem in (23) is given by the transmit Wiener filter approach and can be obtained by the following expression:

$$\mathbf{B} = \tau \left(\hat{\mathbf{H}}^H \mathbf{U}^H \mathbf{W} \mathbf{U} \hat{\mathbf{H}} + \text{dg}(\mathbf{D}) + \frac{\sigma_k^2 \text{tr}(\mathbf{W} \mathbf{U} \mathbf{U}^H)}{\gamma} \mathbf{I} \right)^{-1} \hat{\mathbf{H}}^H \mathbf{U}^H \mathbf{W} \,, \tag{26}$$

where $\mathbf{D} = \mathbf{G}^T \text{diag}(\mathbf{U}^H \mathbf{W} \mathbf{U}) \mathbf{1}_{1 \times B_r}$ is the regularization matrix, which accounts for CSI imperfections. Furthermore, $\mathbf{W} = \text{blkdiag}(\mathbf{W}_1, \cdots, \mathbf{W}_K)$ denotes the overall weighting matrix and the extended error variance matrix $\mathbf{G} = [\mathbf{G}_1, \cdots, \mathbf{G}_K]^T$ with $\mathbf{G}_k = [\mathbf{G}_{k,1}, \cdots, \mathbf{G}_{k,\bar{K}}]$, which consists of the link-wise error variances $\mathbf{G}_{j,\bar{k}} = \epsilon_{j,\bar{k}} \cdot \mathbf{1}_{b_j \times b_{\bar{k}}}$ for all transmission links.



(a) Average throughput for each transmission link



(b) Behavior of outage probability in the outer loop

Fig. 4. Performance evaluation of the proposed method

In order to satisfy the per-BS transmit power constraints, the scaling factor

$$\tau = \max_{j} \sqrt{\gamma_j / tr(\hat{\mathbf{B}}_j \hat{\mathbf{B}}_j^H)} \tag{27}$$

is applied. The proposed algorithm is summarized in pseudo-code in Algorithm 1, where P_d is the maximal allowable transmit power for a device and $\boldsymbol{\epsilon}$ is the error variance matrix.

V. Numerical Result

This section evaluates the performance of the proposed method and compares the results with other state-of-the-art techniques.

We assume that the distance from BS to freeway is 200 meters. There are 3 vehicles in the platoon, $K = 3$. The distance between subsequent vehicles is 10 meters [14]. Every vehicle and every cellular user are equipped with two transceivers. We assume a cellular user in the cell, $M = 1$. The cellular radio propagation is modeled according to an urban macro-cell scenario as defined by 3GPP [15], where the inter-site distance d_I is 500 meters, the fading coefficient is -144.5 dB and the path loss exponent is 3.5. Without loss of generality, the variance of the CSI imperfection is assumed to be $\epsilon_{j,\bar{k}} = 0.1 \cdot \lambda_{j,\bar{k}}$, $\forall\ j, \bar{k}$.

For all algorithms, Monte Carlo simulations with $1,000$ channel realizations, 100 iterations for the outer loop and 100 iterations for the inner loop were computed. Outer loop refers to the alternating computation of precoding matrix and transmission rate, i.e., index i in Algorithm 1. Inner loop corresponds to the calculation of the precoding matrix as given in [12].

Fig. 4(a) compares the performance of our proposed algorithm with the two other reference methods presented in [4] and [5]. These reference methods also address D2D underlay networks and have throughput as the evaluation metric. The difference is that our proposed algorithm designs a method that improves the reliability of the communication link, by carefully optimizing the assigned transmission rate and precoder alternatively; the other two methods design algorithms for throughput maximization without considering reliability. In our proposed algorithm, the throughput is optimized for each transmission link. From the figure, we observe that our proposed algorithm outperforms the comparison methods. At low SNR, the proposed algorithm yields approximately 3 bit/s/Hz more for average throughput over each transmission link than resource sharing method [4] and 4 bit/s/Hz more for average throughput over each transmission link than resource sharing method [5]. Approaching high SNR, the gain in throughput diminishes between the proposed method and the resource sharing method [4] . However, the gain in throughput widens between the proposed method and the resource sharing method [5]. It yields only 1 bit/s/Hz more than [4], but 9 bit/s/Hz more than [5]. The reason for this observation is that at low SNR, outage is more likely to happen. Overall, algorithm that consider outage achieves higher throughput than algorithm that did not consider outage.

Fig. 4(b) shows the convergence of outage probability in the outer loop iterations. It can be observed that our proposed algorithm is able to reduce the outage probability significantly after a few iterations.

VI. Conclusion

In this paper, we have studied the design of precoder in underlay D2D communication sharing uplink resources in a multi-user cellular system, specifically considering vehicle-to-vehicle communication and platooning as a D2D use case that has high requirements on throughput and reliability of communication. We have characterized the precoder in such a way that the D2D link reaches the maximum throughput when CSI is only partially available at devices and transmission could be in outage. We have also compared our proposed method with other state-of-the art algorithms. Numerical examples gained by simulation show that the performance of our proposed method achieves higher average throughput over each transmission link and reduces the outage probability over outer iterations, hence, increasing the reliability of the network.

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