SINR-Outage Minimization of Robust Beamforming for the Non-Orthogonal Wireless Downlink

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***Abstract*—A probabilistically robust transmit beamforming problem is referred, when the wireless downlink (DL) communication is supported by a robust non-orthogonal transmission (NOT)-aided design. Realistic imperfect channel state information (CSI) is considered in the face of rapidly fluctuating vehicular wireless channels, when the road side unit (RSU) communicates with multiple vehicles. Our design objective is to keep the probability of each vehicle's signal-to-interference-plus-noise ratio (SINR) outage below a given threshold. Minimizing the outage probability presents a significant analytical and computational challenge, since it does not lend itself to tractable closed-form expressions. Assuming a Gaussian CSI uncertainty distribution, we provide an approximation method by resorting to the semidefinite relaxation (SDR) and then apply a convex restriction to the original SINR outage constraints. Furthermore, the infinite constraints are reformulated into linear matrix inequalities (LMIs) by exploiting the popular S-procedure. As a benefit, the reformulated program can be solved efficiently using off-the-shelf solvers. Computer simulations are performed for benchmarking our convex method both against the non-robust non-orthogonal as well as the classical orthogonal designs. The results show that our robust beamforming design offers excellent high-mobility performance.**

***Index Terms*—Robust optimization, non-orthogonal multiple access (NOMA), high mobility, channel state information (CSI), outage probability.**

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I. Introduction

A. Background

Vehicular communications and networking (VCN) are capable of significantly improving road traffic efficiency and safety, as well as providing infotainment services [1]. The earliest vehicular network was ratified under the dedicated short range communications (DSRC) standard IEEE 802.11p established at the beginning of this century [2]. At the time of writing, the public access networking based VCN solutions are attracting substantial research attention [3]–[6]. As a benefit of the operational Long Term Evolution (LTE) networks, vehicle-to-everything (V2X) services are already well supported [3], as evidenced by the Third Generation Partnership Project's (3GPP) Release 14 [4]. Additionally, its Release 15 further specifies the service requirements of V2X scenarios [5], [6]. In China, 20 MHz (5905–5925 MHz) of bandwidth has been officially allocated for LTE V2X [1]. Standardization of V2X based on the 5G new radio (NR) also constitutes a further study item.

Technically, however, the research and development of VCN are facing formidable challenges. *Firstly*, the data volume has seen an exponential surge [7], since the connected vehicles have to exchange significant amounts of data in support of safety, navigation and infotainment services. *Secondly*, the pilot overhead has to be doubled every time when the Doppler frequency is doubled [8]. For a wireless terminal operating at a speed of say 150 $\mathrm{km/h}$ at the carrier frequency of 5.9 GHz, the maximum Doppler frequency is 819 Hz, which corresponds to a channel coherence time of approximately 305 μs, if we view a phase change of $\pi/2$ to be significant [9]. This coherence time is lower than the current 500 μs time interval of the reference signals [10]. As a result, the detection performance is substantially degraded. *Thirdly*, the ever-changing network connectivity and topology of VCN incurs frequent handovers, which tend to drop the link if it cannot be completed within its time-out period [8]. This gravely degrades the users' experience. Given the above challenges, it is of salient importance to conceive bandwidth-efficient as well as resilient schemes for hostile vehicular wireless propagation environments.

As a powerful solution, non-orthogonal multiple access (NOMA) has attracted substantial research efforts [11]–[13]. In this paper, the term non-orthogonal transmission (NOT) is used synonymously with NOMA for downlink (DL), since the latter is widely used in the literature. Compared to other non-orthogonal techniques, such as sparse code multiple access (SCMA) and pattern division multiple access (PDMA), NOT-aided power domain multiplexing relies on an appealingly low receiver complexity. To mitigate the multiple access interference (MAI), multi-user detection (MUD) techniques such as successive interference cancellation (SIC) [14] should be applied by the end-user receivers for detecting the desired signals. By relying on NOT-aided power domain multiplexing at the transmitter and SIC at the receivers, the system becomes capable of fully exploiting its capacity region, hence outperforming classic orthogonal transmission schemes [15]. Specifically, the design aspects of non-orthogonal DL and uplink (UL) schemes have been widely discussed. For example, they were considered in a millimeter wave (mmWave) context in [16], in cooperative communications in [17], [18], in multiple-input multiple-output (MIMO) scenarios in [15], [19], in cognitive radios in [20], in vehicular communications in [21], in energy harvesting in [22]–[24], and in mobile edge computing (MEC) in [25]. In this treatise, we focus our attention on the performance improvement of NOT in vehicular scenarios.

B. Related Research and Motivations

A comprehensive review of high-mobility wireless communications and NOMA can be found in [8] and [11], respectively. Specifically, Liu *et al.* [17] investigated the optimal power allocation of NOMA broadcasting/multicasting in the DL, where the transmissions from a base station to vehicles are assisted by road side units (RSUs), acting as relays. In [26], the performance of a full duplex (FD) NOMA V2X communication model was studied, where exact ergodic capacity expressions and their approximate closed-form counterparts were derived. It was shown that FD-NOMA exhibits lower latency performance than half duplex (HD) NOMA and HD-OMA schemes. In [27], a cooperative superposed transmission scheme was proposed based on NOMA for vehicle-to-vehicle (V2V) systems, where multiple vehicles' signals are superposed for re-transmissions and hence improved link reliability is shown to be achievable analytically.

Multiple antenna techniques offer potential benefits in wireless communications through additional degrees of freedom (DoFs), which can be exploited for further enhancing the performance of NOMA [28]. Specifically, the authors of [29] elaborated on the benefits of beamforming techniques in DL of a multiple-input single-output (MISO) NOMA system using optimization methodologies. In [25], a beamforming-aided NOMA solution was exploited in an MEC scenario, where the computational tasks were offloaded to multiple helping users and then transmitted back after processing. Xiao *et al.* [16] focused their research on NOMA in mmWave communications, and optimized both the analog beamforming and power allocation for maximizing the sum rate by decomposing the original problem into two sub-problems. In [30], beam selection was considered in a NOMA system context, with special emphasis on the user mobility, where a narrow beam was preferred by the terminals moving at lower speed. However, all contributions have assumed perfect channel state information (CSI) at the transmitters, which is quite impractical due to the existence of channel estimation errors, quantization errors, feedback delay and so on.

Upon taking the channel uncertainty into consideration, a robust design was conceived for NOMA in [20], [23], [24], [31]–[34]. In [20], [23] and [24], robust beamforming was developed for striking a balance between information transmission and energy harvesting in a NOMA based simultaneous wireless information and power transfer (SWIPT) system. Specifically, both [20] and [23] took the bounded and the Gaussian CSI error models into consideration. In [31], two types of imperfect CSI were considered and MIMO-NOMA was designed for communicating with users in multiple clusters subject to certain outage constraints. Zhao *et al.* [32] studied a robust sum rate optimization problem in a NOMA amplify-and-forward (AF) relay network. In [33], the authors conceived robust beamforming for the NOT-aided multiple-input single-output (MISO) downlink in the face of bounded channel uncertainties in a single-user cluster. Similarly, the authors of [34] proposed a robust NOMA system, where the users were grouped into multiple clusters and the worst-case achievable sum rate was maximized.

Nevertheless, the existing techniques developed for NOMA in VCN primarily considered a quasi-static or moderate mobility scenario [17], [26], [27], [30]. However, given these challenges, there is a paucity of solutions for high-mobility scenarios, even though the high-velocity movement of wireless terminals will seriously impact the CSI acquisition accuracy. The CSI adopted for transmission is no longer perfect, even though perfect CSI has been a common by used assumption, especially for static or low mobility systems. Hence, to solve this open problem, we develop a new transmission scheme, termed as the robust NOT-aided design, which is resilient in vehicular communications even in the face of relatively high velocities.

C. Contributions

In this paper, we study a probabilistically robust beamforming problem at the RSU when transmitting non-orthogonally to multiple vehicles in the DL. We refer to imperfect CSI and CSI uncertainty synonymously. The imperfect CSI is considered to be caused by the realistic channel estimation error and the time delay between the instant of channel estimation and that of exploiting it for beamforming aided DL transmission design. The main objective is to keep the probability of each vehicle's signal-to-interference-plus-noise ratio (SINR) outage below a given threshold. However, satisfying this SINR outage constraint presents a significant analytical and computational challenge, which does not lend itself to a closed-form solution.

Against this background, the main contributions of this paper are three-fold:

- We model the CSI uncertainty in a high-mobility DL scenario, where the effects of both the channel estimation error, of the CSI feedback delay and of the vehicular velocities are all characterized. Based on our model of imperfect CSI, we propose a robust NOT-aided design by formulating an optimization problem to design transmit beamforming for minimizing the total transmit power under SINR outage constraints.

- Assuming a Gaussian CSI uncertainty distribution, we provide an approximation method by applying semidefinite relaxation (SDR) and a convex restriction to the original SINR outage constraints. Furthermore, due to the imperfect CSI, the constraints are infinite, which are reformulated into linear matrix inequalities (LMIs) by exploiting the S-procedure. As a benefit, the reformulated problem can be solved efficiently.
- We benchmark our robust NOT-aided design relying on the SDR, convex restriction and S-procedure conceived both against the conventional non-robust NOT as well as the OMA design. The results show that our SINR-outage-constrained robust NOT-aided beamforming design offers significantly enhanced resilience against high velocities.

The rest of this paper is organized as follows. The system model is given in Section II, where the signal model, channel modeling and problem formulation are detailed. Our overall approach to developing robust beamforming is then discussed in Section III. Our simulation results are provided in Section IV, while conclusions are offered in Section V.

Notation: Uppercase and lowercase bold-faced letters indicate matrices and vectors, respectively. $(\cdot)^{-1}$, $(\cdot)^{H}$, $\det(\cdot)$, and $[\cdot]_{p,q}$ represent inverse, conjugate-transpose, determinant, and the entry in the p-th row and q-column of a matrix, respectively. $\mathbb{E}_X\{\cdot\}$ denotes the expectation on the random variable X. $\mathbf{A} \in \mathbb{C}^{M\times N}$ is a complex-element matrix with dimensions $M \times N$, and $\mathbf{I}_N$ is an $N \times N$ identity matrix. $|\cdot|$ and $(\cdot)^*$ imply the absolute value and the conjugate of a complex scalar, while $\|\cdot\|$ denotes the Euclidean norm of a vector. Finally, $x \sim \mathcal{CN}\left(\mu, \sigma^2\right)$ indicates that the random variable x obeys a complex Gaussian distribution with mean μ and variance σ^2.

II. System Model and Problem Formulation

A. Signal Model

We consider the NOT-based vehicular DL scenario of Fig. 1, where an RSU equipped with N_t DL transmit antennas sends signals to NM vehicles each having a single antenna ($N_t \geq NM$). We assume that these vehicles are grouped into N clusters having M users in each cluster. We use V_{nm} to denote the m-th vehicle in the n-th cluster, with $n \in \mathcal{N} = \{1, \cdots, N\}$ and $m \in \mathcal{M} = \{1, \cdots, M\}$. Let $s_{n,m}(t) \in \mathbb{C}$ represent the signal of interest for V_{nm} associated with $\mathbb{E}[|s_{nm}(t)|^2] = 1$, and $\mathbf{w}_{nm} \in \mathbb{C}^{N_t\times 1}$ denote the associated transmit beamforming vector. The DL transmit signal of the RSU is given by

$$x(t) = \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{M}} \mathbf{w}_{ij}s_{ij}(t). \tag{1}$$

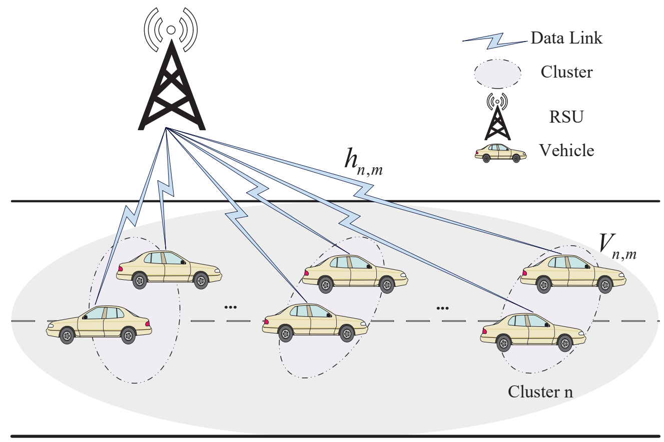


Fig. 1. A NOT-aided downlink vehicular scenario.

The received signal of V_{nm} can be expressed as

$$\begin{aligned} y_{nm}(t) &= d_{nm}^{-\frac{\alpha}{2}}\mathbf{h}_{nm}^H(t)\sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{M}}\mathbf{w}_{ij}s_{ij}(t) + z_{nm}(t) \\ &= d_{nm}^{-\frac{\alpha}{2}}\mathbf{h}_{nm}^H(t)\mathbf{w}_{nm}s_{nm}(t) + d_{nm}^{-\frac{\alpha}{2}}\mathbf{h}_{nm}^H(t)\sum_{\substack{j\in\mathcal{M}\\ j\neq m}}\mathbf{w}_{nj}s_{nj}(t) \\ &\quad + d_{nm}^{-\frac{\alpha}{2}}\mathbf{h}_{nm}^H(t)\sum_{\substack{i\in\mathcal{N}\\ i\neq n}}\sum_{j\in\mathcal{M}}\mathbf{w}_{ij}s_{ij}(t) + z_{nm}(t), \end{aligned} \tag{2}$$

where $\mathbf{h}_{nm}(t) \in \mathbb{C}^{N_t\times 1}$ denotes the channel vector of the link spanning from the RSU to V_{nm}, specifying the small scale fading at time t, d_{nm} is the distance between RSU and V_{nm}, and $\alpha > 0$ indicates the path loss exponent. Here $z_{nm}(t) \in \mathbb{C}$ represents the additive white Gaussian noise (AWGN) at V_{nm}, whose single sideband power spectral density is N_0. As shown in (2), at the right hand side of the second equal sign, the first summation is the desired signal of V_{nm}, while the second and third ones represent the intra- and inter-cluster interference, respectively.

Since the NOMA philosophy is applied, SIC will be carried out at the vehicles. Without loss of generality, we assume that the vehicles in each cluster are sorted based on the CSI so that $\|\mathbf{h}_{n1}\| \leq \|\mathbf{h}_{n2}\| \leq \cdots \leq \|\mathbf{h}_{nM}\|$, for $\forall n \in \mathcal{N}$. Hence V_{nm} should detect the signal of V_{nl} for any $l < m$, i.e., $s_{nl}(t)$, and then remove the associated interference before detecting its desired signal. According to (2), the SINR and the rate of V_{nm} detecting $s_{nl}(t)$ for any $l < m$ are given by

$$\Gamma_{nml} = \frac{\left|\mathbf{h}_{nm}^H\mathbf{w}_{nl}\right|^2}{\sum\limits_{j=l+1}^{M}\left|\mathbf{h}_{nm}^H\mathbf{w}_{nj}\right|^2 + \sum\limits_{\substack{i\in\mathcal{N}\\ i\neq n}}\sum\limits_{j\in\mathcal{M}}\left|\mathbf{h}_{nm}^H\mathbf{w}_{ij}\right|^2 + d_{nm}^{\alpha}N_0B} \tag{3}$$

$$R_{nml} = B\log\left(1 + \Gamma_{nml}\right), \tag{4}$$

respectively, where B is the total bandwidth allocated for vehicular DL transmissions. After successful SIC, the SINR and rate of V_{nm} detecting its desired signal $s_{nm}(t)$ are

$$\Gamma_{nmm} = \frac{\left|\mathbf{h}_{nm}^H \mathbf{w}_{nm}\right|^2}{\sum_{j=m+1}^{M} \left|\mathbf{h}_{nm}^H \mathbf{w}_{nj}\right|^2 + \sum_{\substack{i\in\mathcal{N}\\ i\neq n}} \sum_{j\in\mathcal{M}} \left|\mathbf{h}_{nm}^H \mathbf{w}_{ij}\right|^2 + d_{nm}^{\alpha} N_0 B}, \quad (5)$$

$$R_{nmm} = B \log\left(1 + \Gamma_{nmm}\right), \quad (6)$$

respectively.

B. Channel Modeling

As above mentioned, we consider two main causes of imperfect CSI in the robust NOT-aided design for VCN. One of them is the channel estimation error imposed by the channel estimation process. In high mobility systems it becomes more serious due to the rapidly time-varying nature of the channel. Hence, it becomes more necessary to take the channel estimation error into consideration in our robust NOT-aided transceiver designed for high mobility. The other is the deleterious effects of the Doppler spread. It should be noted that in wireless communication systems the downlink channel is estimated at the receiver and then fed back to the transmitter via an UL control channel. Hence, there is a feedback delay between the instant of CSI estimation and the actual transmit beamforming, during which further aggravates the CSI uncertainty.

As denoted, the channel vector $\mathbf{h}_{nm}(t)$ specifies the small-scale fading at time t. As discussed in the introduction section, in a high-mobility scenario, the RSU endures fast-varying CSI. Explicitly, we express the exact CSI $\mathbf{h}_{nm}(t)$ associated with $\hat{\mathbf{h}}_{nm}(t-\tau)$, which is the estimated CSI at time instant $(t-\tau)$, with an auto regressive model [8] of

$$\mathbf{h}_{nm}(t) = \rho_{nm}\hat{\mathbf{h}}_{nm}(t-\tau) + \mathbf{e}_{nm}(t), \forall n \in \mathcal{N}, m \in \mathcal{M}, \quad (7)$$

where ρ_{nm} is a model's evolution parameter, characterizing the impact of the Doppler effect. Here $\mathbf{e}_{nm}(t) \in \mathbb{C}^{N_t\times 1}$ indicates the model uncertainty, whose distribution obeys $\mathcal{CN}\left(0, \mathbf{C}_{nm}\right)$. Specifically, $\mathbf{C}_{nm}$ is a Hessian positive-definite matrix of $N_t \times N_t$ dimensions. For notational simplicity, we omit the time label t and $(t-\tau)$. An alternative expression of $\mathbf{e}_{nm}$ is

$$\mathbf{e}_{nm} = \mathbf{C}_{nm}^{1/2}\mathbf{v}_{nm}, \quad (8)$$

where $\mathbf{v}_{nm}$ is a normalized random vector obeying the complex Gaussian distribution of $\mathcal{CN}\left(0, \mathbf{I}_{N_t}\right)$.

For the model's evolution parameter ρ_{nm}, we use Jake's model to characterize the time-varying wireless channels. More explicitly, Jake's model may be viewed as a simulation based implementation of Clarke's two-dimensional isotropic scattering model, which assumes that the wireless signals propagate in a 2-D plane and arrive at the receiver from all directions with equal probability [9]. Under the assumption of wide sense stationary uncorrelated scattering, ρ_{nm} is given by

$$\rho_{nm} = J_0\left(\frac{2\pi f_c v_{nm}}{c}\tau\right), \quad (9)$$

where f_c is the carrier frequency, v_{nm} is the relative velocity between V_{nm} and the RSU, the function $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind, c is the light speed, and τ is the time delay between the instant of the receiver's channel estimation and the actual DL transmission instant, which can be further expressed as $\tau{=}\frac{k}{R_s}$ with k indicating the number of symbols in these time intervals and R_s denoting the transmit symbol rate. For the statistics of the CSIs, we have

$$\begin{aligned} &\mathbb{E}\left[\left\|\mathbf{h}_{nm}\right\|^2\right] \\ &= \mathbb{E}\left[\left\|\rho_{nm}\hat{\mathbf{h}}_{nm} + \mathbf{e}_{nm}\right\|^2\right] \\ &= \mathbb{E}\left[\rho_{nm}^2\left\|\hat{\mathbf{h}}_{nm}\right\|^2 + 2\rho_{nm}\mathrm{Re}\left(\hat{\mathbf{h}}_{nm}^H\mathbf{e}_{nm}\right) + \left\|\mathbf{e}_{nm}\right\|^2\right] \\ &= \rho_{nm}^2\mathbb{E}\left[\left\|\hat{\mathbf{h}}_{nm}\right\|^2\right] + \mathbb{E}\left[\left\|\mathbf{e}_{nm}\right\|^2\right] \\ &= \rho_{nm}^2\mathbb{E}\left[\left\|\hat{\mathbf{h}}_{nm}\right\|^2\right] + \mathrm{Tr}\left(\mathbf{C}_{nm}\right). \end{aligned} \quad (10)$$

In general, we assume that $\mathbf{h}_{nm}$ and $\hat{\mathbf{h}}_{nm}$ are all zero-mean unit-variance complex Gaussian random vectors. Hence, from (10), we can associate $\mathbf{C}_{nm}$ with the influence of high mobility formulated as

$$\mathrm{Tr}\left(\mathbf{C}_{nm}\right) = \left(1-\rho_{nm}^2\right)N_t. \quad (11)$$

A simplified model of the CSI uncertainties is $\mathbf{e}_{nm} \sim \mathcal{CN}\left\{0, \mathbf{C}_{nm}\right\}$ with $\mathbf{C}_{nm} = \varepsilon_{nm}^2\mathbf{I}_{N_t}$, where $\varepsilon_{nm} > 0$ is assumed. Alternatively, for such a simplified consideration, we have $\mathbf{e}_{nm} = \varepsilon_{nm}\mathbf{v}_{nm}$ and

$$\varepsilon_{nm} = \sqrt{1-\rho_{nm}^2}. \quad (12)$$

C. Problem Formulation

In this paper, we use the minimum rate requirement as the user's quality of service (QoS). Specifically, for the signal $s_{nm}(t)$, we assume that it is only deemed to be detected successfully, provided that the received rate meets the minimum rate requirement $\bar{R}_{nm}$; otherwise a transmission outage event would be declared. Hence, an outage probability constraint is also included, which requires that the signal $s_{nm}(t)$ should be detected reliably, whilst having a rate no lower than $\bar{R}_{nm}$ at least $(1-p_{nm}) \times 100\%$ of the time. Explicitly, $p_{nm} \in (0,1]$ specifies the maximum tolerable outage probability, representing a rate lower than the target upon detecting the signal $s_{nm}(t)$. Alternatively, the minimum rate requirement $\bar{R}_{nm}$ means that the SINR received at a certain receiver falls below the SINR requirement of

$$\gamma_{nm} = 2^{\bar{R}_{nm}/B} - 1. \quad (13)$$

Accordingly, the condition of having a successful SIC action at V_{nm} is that the SINR is above the target with a given probability, which is formulated as

$$\mathrm{Pr}_{\mathbf{h}_{nm}\sim\mathcal{CN}\left(\rho_{nm}\hat{\mathbf{h}}_{nm}, \mathbf{C}_{nm}\right)}\left\{\Gamma_{nml} \geq \gamma_{nl}\right\} \geq 1 - p_{nl} \quad (14)$$

for any $m, l \in \mathcal{M}$ and $l < m$. More particularly, when $l = m$, (14) represents the SINR-outage-constrained condition that V_{nm} succeeds in detecting its desired signal.

Our goal is to minimize the transmit power of the RSU by optimizing the beamforming weights for satisfying the

SINR requirement for all possible CSI errors without violating the outage probability constraint. Hence, we consider the following robust NOT-aided beamforming design

$$\begin{aligned}\mathcal{P}_0 : &\min_{\{\mathbf{w}_{n,m}\}} \sum_{n\in\mathcal{N}}\sum_{m\in\mathcal{M}} \|\mathbf{w}_{n,m}\|^2\\ s.t.\ &\Pr_{\mathbf{h}_{nm}\sim\mathcal{CN}(\rho_{nm}\hat{\mathbf{h}}_{nm},\mathbf{C}_{nm})}\{\Gamma_{nml}\geq\gamma_{nl}\}\geq 1-p_{nl}\\ &\forall n\in\mathcal{N},\ m,l\in\mathcal{M},\ m\geq l.\end{aligned} \tag{15}$$

Solving the robust design problem (15) is challenging, since, on the one hand, each of the SINR constraints $\Gamma_{nml}\geq\gamma_{nl}$ is non-convex as implied by (3) and (5). On the other hand, these outage probability constraints do not admit a closed-form solution and are unlikely to be efficiently computable in general [35]. In the next section, we will discuss the optimization techniques of SDR, convex restriction and S-procedure to handle problem (15).

III. Robust DL Transmit Beamforming Design

In this section, we provide an approximation method relying on SDR and a convex restriction imposed on the original SINR outage constraints. Since the constraints are infinite essentially, we reformulate them into LMIs by exploiting S-procedure. Hence, the reformulated problem can be solved efficiently.

A. Semidefinite Relaxation

Considering that each of the SINR constraints is non-convex, we first apply SDR to (15). Specifically, we express the objective function of (15) as $\sum_{n\in\mathcal{N}}\sum_{m\in\mathcal{M}}\mathrm{Tr}\left(\mathbf{w}_{nm}\mathbf{w}_{nm}^H\right)$. To apply the SDR technique, we replace the rank-one matrix $\mathbf{w}_{nm}\mathbf{w}_{nm}^H$ by a general-rank positive semidefinite matrix $\mathbf{W}_{nm}$ of $N_t\times N_t$ dimensions. After SDR, (15) is reformulated as (16), shown at the top of this page. Substituting $\mathbf{h}_{nm}=\rho_{nm}\hat{\mathbf{h}}_{nm}+\mathbf{e}_{nm}$ and $\mathbf{e}_{nm}=\mathbf{C}_{nm}^{1/2}\mathbf{v}_{nm}$ into (16), it can be alternatively expressed as (17), shown at the top of the next page. Observe in (17) that this problem $\mathcal{P}_2$ has infinite constraints and none of the probabilistic constraints facilitates the derivation of an analytical closed-form expression for the probability function. Fortunately, the probabilistic constraints can be handled in a conservative manner [23]. In this context, the key idea is essentially to find another probability constraint, that constitutes a sufficient condition for the original probability to hold true, and equally importantly, it is convex. Then we can replace the probability constraint in (17), whilst ensuring that the resultant SINR constraint satisfaction probability will be higher.

B. Convex Restriction

The so-called sphere-bounding approach [35] is introduced subsequently, which can lead to a conservative convex constraint approximation of problem $\mathcal{P}_2$ in (17), implying that if the resultant convex constraint is satisfied, then the constraints in (17) are also satisfied. To elaborate a little further, the sphere bounding approach is based on the following lemma.

***Lemma* 1:** Let $\mathbf{v}\in\mathbb{C}^{N_t}$ be a continuous random vector following certain statistical distribution and $G(\mathbf{v}):\mathbb{C}^{N_t}\to\mathbb{R}$ be a function of $\mathbf{v}$. Let $r>0$ be the radius of the sphere $\left\{\mathbf{v}\,\middle|\,\|\mathbf{v}\|^2\leq r^2\right\}$, that we have $\Pr\left\{\mathbf{v}\,\middle|\,\|\mathbf{v}\|^2\leq r^2\right\}\geq(1-p)$, where $p\in(0,1]$. Then having $G(\mathbf{v})\geq 0$ for $\forall\|\mathbf{v}\|^2\leq r^2$ implies $\Pr\{G(\mathbf{v})\geq 0\}\geq(1-p)$.

Before applying Lemma 1, we introduce the shorthand

$$G(\mathbf{v}_{nm})=\mathbf{v}_{nm}^H\mathbf{Q}_{nml}\mathbf{v}_{nm}+2\mathrm{Re}\left\{\mathbf{v}_{nm}^H\mathbf{u}_{nml}\right\}-c_{nml}. \tag{18}$$

For the outage constraint in (17), we achieve the following implications

$$\begin{aligned}&G(\mathbf{v}_{nm})\geq 0,\ \forall\|\mathbf{v}_{nm}\|^2\leq r_{nl}^2\\ &\Rightarrow\Pr\left\{\mathbf{v}_{nm}^H\mathbf{Q}_{nml}\mathbf{v}_{nm}+2\mathrm{Re}\left\{\mathbf{v}_{nm}^H\mathbf{u}_{nml}\right\}\geq c_{nml}\right\}\geq 1-p_{nl},\end{aligned}$$

where $r_{nl}>0$ is the radius of the norm sphere $\left\{\mathbf{v}_{nm}\,\middle|\,\|\mathbf{v}_{nm}\|^2\leq {r_{nl}}^2\right\}$ so that

$$\Pr\left\{\mathbf{v}_{nm}\,\middle|\,\|\mathbf{v}_{nm}\|^2\leq r_{nm}^2\right\}\geq(1-p_{nl}).$$

For the case of $\mathbf{v}_{nm}\sim\mathcal{CN}(0,\mathbf{I}_{N_t})$, $2\|\mathbf{v}_{nm}\|^2$ is a Chi-square distributed random variable with associated $2N_t$ degrees of freedom. Let $F^{-1}(\cdot)$ denote the inverse cumulative distribution function of $2\|\mathbf{v}_{nm}\|^2$. Then it can be shown that r_{nl} is given by

$$r_{nl}=\sqrt{\frac{F^{-1}(1-p_{nl})}{2}}. \tag{19}$$

Hence, satisfying $G(\mathbf{v}_{nm})\geq 0$ for $\forall\|\mathbf{v}_{nm}\|^2\leq r_{nl}^2$ is sufficient to guarantee that $\Pr\{G(\mathbf{v}_{nm})\}\geq(1-p_{nl})$. After applying aforementioned sphere bounding approach, the problem (17) is reformulated into

$$\begin{aligned}\mathcal{P}_3 : &\min_{\{\mathbf{W}_{nm}\}}\sum_{n\in\mathcal{N}}\sum_{m\in\mathcal{M}}\mathrm{Tr}(\mathbf{W}_{nm})\\ s.t.\ &\mathbf{v}_{nm}^H\mathbf{Q}_{nml}\mathbf{v}_{nm}+2\mathrm{Re}\left\{\mathbf{v}_{nm}^H\mathbf{u}_{nml}\right\}\geq c_{nml}\\ &\|\mathbf{v}_{nm}\|^2\leq r_{nl}^2,\mathbf{W}_{nm}\succeq\mathbf{0}\\ &\forall n\in\mathcal{N},m,l\in\mathcal{M},m\geq l.\end{aligned} \tag{20}$$

C. S-Procedure

Now the problem (20) is convex, since both the objective function and the constraints are all linear in $\mathbf{W}_{nm}$. However, (20) is still computationally intractable because it involves an infinite number of constraints. Fortunately, the infinitely many constraints exhibit the quadratic form, and can be recast into finite LMIs with a number of unknown non-negative parameters. This reformulation is named as *S-procedure* classically [36]. Specifically, by applying the S-procedure, (20) is alternatively expressed as

$$\begin{aligned}\mathcal{P}_4 : &\min_{\{\mathbf{W}_{nm}\},\{\lambda_{nml}\}}\sum_{n\in\mathcal{N}}\sum_{m\in\mathcal{M}}\mathrm{Tr}(\mathbf{W}_{nm})\\ s.t.\ &\mathbf{\Phi}_{nml}\succeq\mathbf{0}\\ &\lambda_{nml}\geq 0,\mathbf{W}_{nm}\succeq\mathbf{0}\\ &\forall n\in\mathcal{N},m,l\in\mathcal{M},m\geq l,\end{aligned} \tag{21}$$

where

$$\mathbf{\Phi}_{nml}=\begin{bmatrix}\mathbf{Q}_{nml}+\lambda_{nml}\mathbf{I}_{N_t} & \mathbf{u}_{nml}\\ \mathbf{u}_{nml}^H & -c_{nml}-\lambda_{nml}r_{nl}^2\end{bmatrix} \tag{22}$$

$$
\begin{aligned}
\mathcal{P}_1: & \min_{\{\mathbf{W}_{nm}\}} \sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} \operatorname{Tr}(\mathbf{W}_{nm}) \\
s.t. \quad & \Pr\left\{ \mathbf{h}_{nm}^H \left(\frac{1}{\gamma_{nl}} \mathbf{W}_{nl} - \sum_{j=l+1}^{M} \mathbf{W}_{nj} - \sum_{\substack{i\in N \\ i\neq n}} \sum_{j\in M} \mathbf{W}_{ij} \right) \mathbf{h}_{nm} \geq d_{nm}^{\alpha} N_0 B \right\} \geq 1 - p_{nl}, \\
& \mathbf{e}_{n,m} \sim \mathcal{CN}\{0, \mathbf{C}_{nm}\}, \mathbf{W}_{nm} \succeq \mathbf{0} \\
& \forall n \in \mathcal{N}, m, l \in \mathcal{M}, m \geq l
\end{aligned} \tag{16}
$$

$$
\begin{aligned}
\mathcal{P}_2: & \min_{\{\mathbf{W}_{nm}\}} \sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} \operatorname{Tr}(\mathbf{W}_{nm}) \\
s.t. \quad & \Pr\left\{ \mathbf{v}_{nm}^H \mathbf{Q}_{nml} \mathbf{v}_{nm} + 2\operatorname{Re}\left\{ \mathbf{v}_{nm}^H \mathbf{u}_{nml} \right\} \geq c_{nml} \right\} \geq 1 - p_{nl}, \\
& \mathbf{v}_{nm} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_{N_t}), \mathbf{W}_{n,m} \succeq \mathbf{0} \\
& \forall n \in \mathcal{N}, m, l \in \mathcal{M}, m \geq l
\end{aligned} \tag{17}
$$

with

$$
\mathbf{Q}_{nml} = \mathbf{C}_{nm}^{1/2} \left(\frac{1}{\gamma_{nl}} \mathbf{W}_{nl} - \sum_{j=l+1}^{M} \mathbf{W}_{nj} - \sum_{\substack{i\in\mathcal{N} \\ i\neq n}} \sum_{j\in\mathcal{M}} \mathbf{W}_{ij} \right) \mathbf{C}_{nm}^{1/2}
$$

$$
\mathbf{u}_{nml} = \rho_{nm} \mathbf{C}_{nm}^{1/2} \left(\frac{1}{\gamma_{nl}} \mathbf{W}_{nl} - \sum_{j=l+1}^{M} \mathbf{W}_{nj} - \sum_{\substack{i\in\mathcal{N} \\ i\neq n}} \sum_{j\in\mathcal{M}} \mathbf{W}_{ij} \right) \hat{\mathbf{h}}_{nm}
$$

$$
c_{nml} = d_{nm}^{\alpha} N_0 B - \rho_{nm}^2 \hat{\mathbf{h}}_{nm}^H \left(\frac{1}{\gamma_{nl}} \mathbf{W}_{nl} - \sum_{j=l+1}^{M} \mathbf{W}_{nj} - \sum_{\substack{i\in\mathcal{N} \\ i\neq n}} \sum_{j\in\mathcal{M}} \mathbf{W}_{ij} \right) \hat{\mathbf{h}}_{nm}
$$

---

represent the LMIs. Observe that in (21), there are $N\sum_{q=1}^{M} q$ different $\mathbf{\Phi}_{nml}$ in total, and each one is of $(N_t+1)\times(N_t+1)$ dimensions. Intrinsically, (21) is a convex semidefinite programming (SDP) problem, and can be solved efficiently by off-the-shelf convex solvers such as CVX [37].

Once the SDP (21) is solved, its solution $\{\mathbf{W}_{nm}^*\}$ is used for finding an approximation to the solution of the original problem (15). If all the optimal solutions $\mathbf{W}_{nm}^*$ are indeed of rank one, decomposing $\mathbf{W}_{nm}^* = \mathbf{w}_{nm}^* \mathbf{w}_{nm}^{*H}$ is straightforward for obtaining the solution $\mathbf{w}_{nm}^*$ of (15). If at least one $\mathbf{W}_{nm}^*$ is not of rank-one, it is conventional to find an approximation appropriately guided by $\mathbf{W}_{nm}^*$. A commonly used popular approximation is Gaussian randomization. Below we elaborate on the detailed procedure.

- *Gaussian randomization*: For the case that $\mathbf{W}_{nm}^*$ is not of rank-one, we generate K random vectors $\left\{\mathbf{x}^{(k)}, k=1,\cdots,K\right\}$ by the Gaussian randomization of $\mathbf{W}_{nm}^*$, then choose $\mathbf{x}^{(k^*)}$ as an approximate solution of $\mathbf{w}_{nm}^*$, where we have

$$
k^* = \arg\min_{k\in\{1,\cdots,K\}} \left(\mathbf{x}^{(k)}\right)^H \mathbf{x}^{(k)} - \operatorname{Tr}(\mathbf{W}_{nm}^*). \tag{23}
$$

D. Performance Analysis of the Proposed Convex Restriction Method

Optimality: Since we handle the SINR outage constraints in a conservative manner, the resultant probability of SINR satisfaction will be higher and may be much higher than the specified value, and meanwhile the total transmit power will also be higher than the optimal transmit power of the original problem. Obviously, the solution provided by the proposed method is suboptimal with respect to (w.r.t.) the original problem $\mathcal{P}_0$ as shown in (15).

Convergence: The convex restriction formulation (21) involves only LMIs. As such, it can be solved by a standard interior point method (IPM). Hence, the proposed method guarantees convergence to the optimal solution of (21), which is suboptimal w.r.t. the original problem.

Complexity: Recall that the proposed convex restriction method involves only LMI constraints, which can be solved by a standard IPM. According to the complexity analysis of IPM-based convex restriction methods provided in [35], the complexity for solving $\mathcal{P}_4$ as shown in (21) is on the order of

$$
\sqrt{2m(N_t+1)}n\times \left[m\left((N_t+1)^3+N_t^3+1\right)+mn\left((N_t+1)^2+N_t^2+1\right)+n^2\right]
$$

where $m=MN$ and $n=\mathcal{O}\left(MNN_t^2\right)$.

IV. Simulation Results and Analysis

A. Simulation Settings

To assess the performance of the proposed robust beamforming design, we consider an RSU serving $N = 2$ clusters, in each of which $M = 2$ vehicles are paired. For simplicity, we term the distant vehicles, i.e., V_{11} and V_{21}, as *cell-edge* users, while the near vehicles V_{12} and V_{22} as *cell-center* users. The RSU is configured to have $N_t = 4$ antennas. For convenience, $d_{11} = d_{21} = 50$ m and $d_{12} = d_{22} = 10$ m, while the path-loss exponent is set to 3. For the small scale fading, we consider a complex Gaussian random distribution with zero mean and unit variance. It is assumed that the RSU can accurately track the large scale fading, and only suffers from small scale CSI errors. The velocities of vehicles are set to $v_{nm} = 150$ km/h, as in practical considerations especially for highway scenarios.

We assume that the total bandwidth allocated to the vehicular downlink transmission system is $B = 20$ MHz and the carrier frequency is set to 5.9 GHz, which are the official settings for the validation of LTE V2X in China [1]. The number of symbols transmitted during the CSI feedback is assumed to be $k = 500$, which corresponds to a time duration of 25 μs. All transceivers have the same noise power spectral density of $N_0 = -174$ dBm/Hz (around -101 dBm over a 20 MHz bandwidth). For the CSI uncertainty, we adopt the simplified model $\mathbf{e}_{nm} \sim \mathcal{CN}\{0, \mathbf{C}_{nm}\}$ associated with $\mathbf{C}_{nm} = \varepsilon_{nm}^2 \mathbf{I}_{N_t}$. If not mentioned specifically, all $\{\varepsilon_{nm}\}$ are the same and equal to ε. For the maximum tolerable transmission rate outage probability upon detecting the signal $s_{nm}(t)$, we set $p_{nm} = 0.1$ for all $n \in \mathcal{N}$ and $m \in \mathcal{M}$, which is equivalent to having a 90% or higher chance of satisfying the minimum rate requirements.

For reference purposes, we run a conventional perfect-CSI-based minimum-SINR NOT-aided design, which is termed as *non-robust NOT* for convenience. Specifically, the associated problem is formulated as

$$\begin{aligned} &\min_{\{\mathbf{w}_{nm}\}} \sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} \|\mathbf{w}_{nm}\|^2 \\ &s.t. \frac{\left|\hat{\mathbf{h}}_{nm}^H \mathbf{w}_{nl}\right|^2}{\sum_{j=l+1}^{M} \left|\hat{\mathbf{h}}_{nm}^H \mathbf{w}_{nj}\right|^2 + \sum_{\substack{i\in\mathcal{N}\\ i\neq n}} \sum_{j\in\mathcal{M}} \left|\hat{\mathbf{h}}_{nm}^H \mathbf{w}_{ij}\right|^2 + d_{nm}^{\alpha} N_0 B} \\ &\qquad \geq \gamma_{nl} \\ &\quad \forall n \in \mathcal{N}, m, l \in \mathcal{M}, m \geq l. \end{aligned} \tag{24}$$

Upon applying SDR to (24), we arrive at the following problem

$$\begin{aligned} &\min_{\{\mathbf{W}_{nm}\}} \sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} \mathrm{Tr}\left(\mathbf{W}_{nm}\right) \\ &s.t. \quad \hat{\mathbf{h}}_{nm}^H \Big(\frac{1}{\gamma_{nl}} \mathbf{W}_{nl} - \sum_{j=l+1}^{M} \mathbf{W}_{nj} - \sum_{\substack{i\in\mathcal{N}\\ i\neq n}} \sum_{j\in\mathcal{M}} \mathbf{W}_{ij}\Big) \hat{\mathbf{h}}_{nm} \\ &\qquad \geq d_{nm}^{\alpha} N_0 B \\ &\quad \mathbf{W}_{nm} \succeq \mathbf{0} \\ &\quad \forall n \in \mathcal{N}, m, l \in \mathcal{M}, m \geq l, \end{aligned} \tag{25}$$

where the objective function and the finite number of constrains are all affine in $\mathbf{W}_{nm}$ and can be solved efficiently by off-the-shelf convex solvers. The rank-one solution can be obtained by exploiting aforementioned Gaussian randomization.

Meanwhile, a pair of robust and a non-robust OMA designs are also considered to augment the benefits of our solutions, where OMA is applied within each cluster and co-channel transmission is employed by the different clusters. For simplicity, we consider frequency division multiple access (FDMA) where M vehicles of a cluster are allocated within an equal bandwidth of B/M orthogonaly. In OMA, the SINR requirement associated with the minimum-rate-constraint $\bar{R}_{nm}$ becomes

$$\gamma_{nm}^{\mathrm{OMA}} = 2^{M\bar{R}_{nm}/B} - 1. \tag{26}$$

Hence, the robust OMA design is formulated as

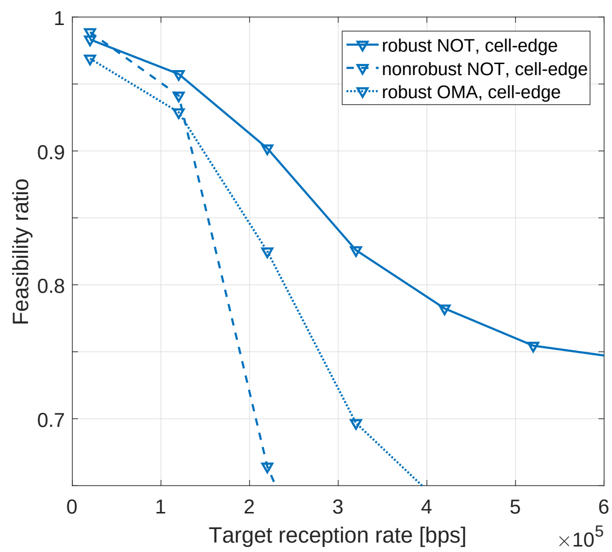
$$\begin{aligned} &\min_{\{\mathbf{w}_{nm}\}} \sum_{n\in\mathcal{N}} \sum_{m\in\mathcal{M}} \|\mathbf{w}_{nm}\|^2 \\ &s.t. \ \Pr_{\rho_{nm}\mathbf{h}_{nm} \sim \mathcal{CN}(\hat{\mathbf{h}}_{nm}, \mathbf{C}_{nm})} \\ &\left\{ \frac{\left|\mathbf{h}_{nm}^H \mathbf{w}_{nm}\right|^2}{\sum_{i\neq n} \left|\mathbf{h}_{nm}^H \mathbf{w}_{im}\right|^2 + d_{nm}^{\alpha} N_0 B/M} \geq \gamma_{nm}^{\mathrm{OMA}} \right\} \geq 1 - p_{nl} \\ &\quad \forall n \in \mathcal{N}, \ m \in \mathcal{M}. \end{aligned} \tag{27}$$

Solving (27) follows similar methodologies to our robust NOT-aided design, which has been elaborated on above.

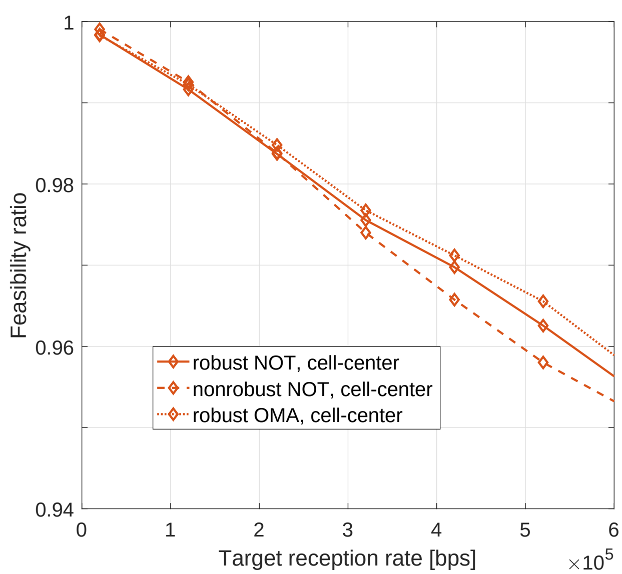
B. Simulation Outputs

We first investigate the chance of finding a feasible solution to our constrained minimization-rate-optimization problem. Figure 2 presents the simulation results obtained both for cell-edge and cell-center users. Observe from this figure that for the cell-edge users our robust NOT design exhibits much higher feasible solution rate than the benchmarks. This explicitly demonstrates the improved capability of our robust transmit beamforming by exploiting the degrees of freedom provided by the multi-antenna aided DL transmitter. For the cell-center users, the performance of our proposed design is slightly degraded. This figure shows that our robust NOT-aided design substantially benefits the terminals, especially when suffering from hostile wireless channel conditions.

Next, let us examine the resilience of our beamforming designs to high velocities. In Fig. 3, we depict the ratio of finding feasible solutions versus the velocity. It can be observed in Fig. 3 that within the moderate to high-velocity intervals, our proposed robust NOT-aided design exhibits the best resilience versus velocity both for cell-edge (Fig. 3(a)) as well as for cell-center users (Fig. 3(b)) by showing the highest feasibility ratio. Let us scritinize Fig. 3(a) more closely. When $v_{nm} \leq$ 75km/h or $v_{nm} \geq$ 115km/h, all robust schemes clearly outperforms their counterparts, where robust NOT exhibits the highest resilience. In 75km/h $\leq v_{nm} \leq$ 115km/h, a non-robust NOT design shows better performance. This observation indicates that our proposed design is suitable for relatively high mobility. By contrast, as shown in Fig. 3(a)

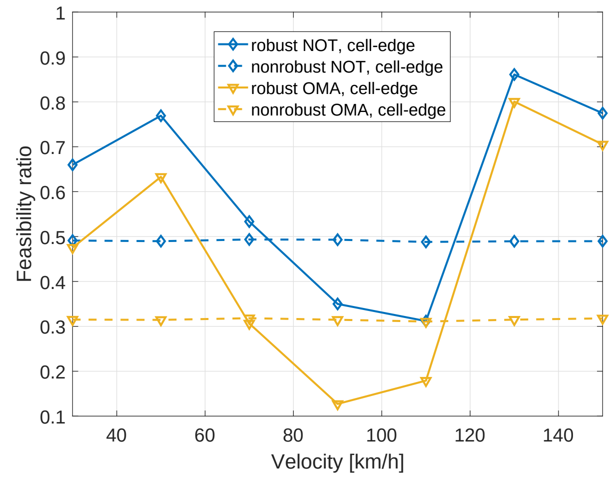


(a)

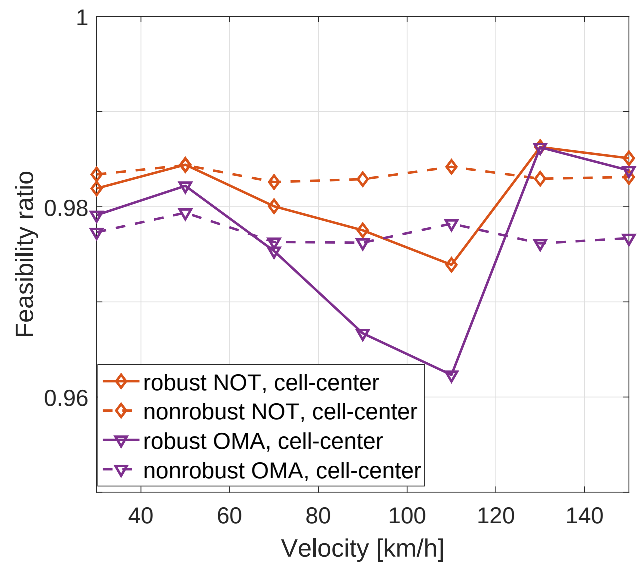


(b)

Fig. 2. Feasibility performance versus target reception rates: (a) cell-edge user; (b) cell-center user.



(a)



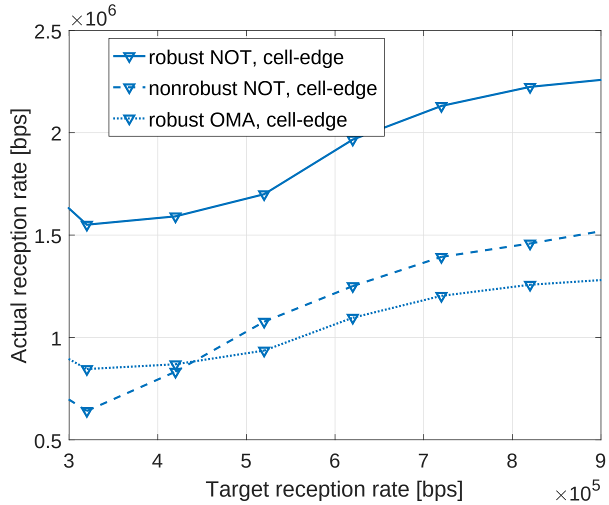
(b)

Fig. 3. Feasibility performance versus velocities with target reception rate being 200 kbps: (a) cell-edge user; (b) cell-center user.

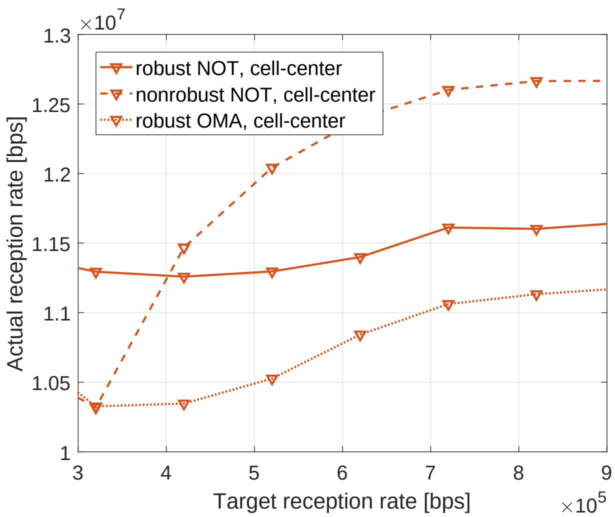
and Fig. 3(b), the overall performance of OMA schemes is generally degraded compared to the NOT arrangements.

To further quantify the benefits of the proposed design, in Fig. 4 we portray the actual reception rate of multiple beamforming schemes. Clearly, for the cell-edge terminals, the robust NOT design exhibits better performance than the benchmarkers, substantially improving the actual reception rate. By contrast, the performance of the cell-center users is slightly degraded compared to the non-robust NOT, but still outperforming the OMA schemes. This observation can be explained as follows: the NOT regime and the consideration of robustness in our proposed design improve both the fairness between different receivers and the resilience against high-velocity mobility. Hence the cell-edge users show enhanced performance. As a benefit of the improved robustness, the additional power improves the performance (as shown in Fig. 5), whilst that of the cell-center users is moderately degraded, which is a widely accepted phenomenon in NOT schemes [11]. As for the sum-rate performance, our proposed design shows significant improvements over its OMA counterparts. By contrast, the sum-rate shown in Fig. 4(c) becomes slightly inferior to that of the conventional non-robust NOT regime at high target reception rates, but our robust NOT scheme has the edge within the moderate target-rate region.

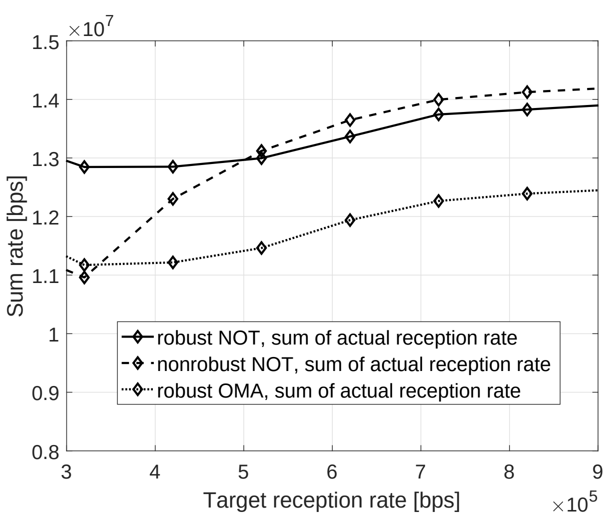
In addition to the feasibility performance and actual reception rate, it is important to examine the transmit power consumption of the various methods. Figure 5 shows the transmit power of multiple beamforming designs versus the target reception rate, indicating that the robust design is power-thirsty. Compared to the non-robust NOT regime, we can get an impression of how much additional transmit power would



(a)



(b)



(c)

Fig. 4. Actual reception rates versus target reception rates: (a) cell-edge user; (b) cell-center user; (c) sum rate performance.

be needed for the robust methods to accommodate the outage specification in the face of imperfect CSI and high velocities.

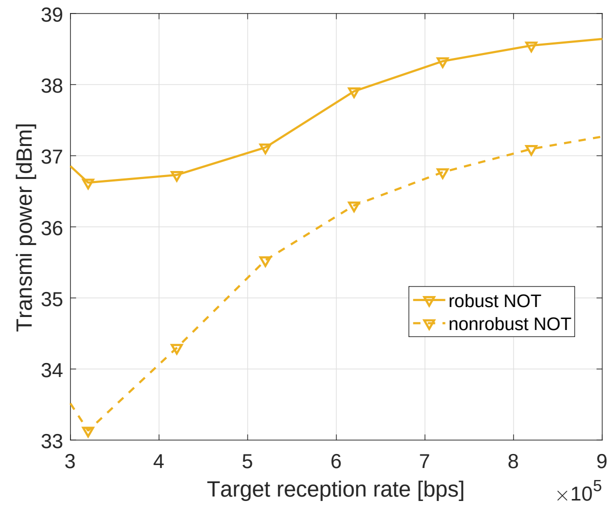


Fig. 5. Transmit power versus target reception rates.

V. Conclusions

In this paper, we have studied a probabilistically robust transmit beamforming problem at the RSU, when transmitting to multiple vehicles in the DL using our robust NOT-aided design. Explicitly, we have modeled the channel uncertainty effects imposed on the NOT-aided DL in a high-mobility scenario, where only imperfect CSI is available at the RSU. The impact of the channel estimation error, CSI feedback delay and vehicular velocities were incorporated. Based on imperfect CSI modeling, we have formulated the optimization problem of our robust transmit beamforming for minimizing the probability of each vehicle's SINR outage to keep it below a given threshold. Assuming Gaussian distributed imperfect CSI, an approximation method has been provided by applying SDR and by imposing a convex restriction on the original SINR outage constraints. The infinite constraints have been further reformulated into LMIs by exploiting the classic S-procedure. Our simulation results have shown that our robust beamforming design offers significantly improved resilience against high velocities.

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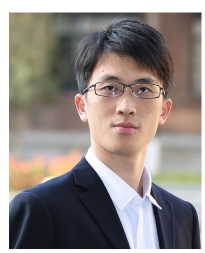

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