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Research article

NOMA for V2X under similar channel conditions

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Abstract: The research on connected vehicles is undergoing a paradigm shift from vehicle-to-vehicle (V2V) to vehicle-to-everything (V2X) communication. However, the existing proposals for V2X rely mainly on conventional orthogonal multiple access (OMA), which utilises the available resources in an orthogonal manner. Consequently, V2X based on OMA may not be able to meet the V2X requirements under dense traffic environments. In this paper, we consider V2X based on non-orthogonal multiple access (NOMA), where several vehicles approach towards a road junction from different directions. Under this scenario, the vehicles at the cross road/junction have very similar channel conditions with the roadside unit (RSU). This poses a challenge to apply NOMA under this scenario because the performance of NOMA is highly dependent upon having significant channel gain difference among users. In order to apply NOMA more effectively under such situation, we propose two channel gain stretching (CGS) strategies inspired by digital image processing to obtain a significant difference among channel gains of the vehicles. In order to evaluate the performance, we derive a closed-form expression of the outage probability. Numerical results are also presented to validate the accuracy of the derived results and also to compare the performance of NOMA with and without both CGS schemes, and OMA.

Keywords: channel gain stretching; non-orthogonal multiple access; power allocation; vehicle-to-everything

1. Introduction

In recent years, the intelligent transportation system (ITS) has evolved to provide driver assistance mechanisms, resulting in enhanced road safety and traffic efficiency. In this regard, much attention has been paid by academia researchers, telecommunication industry and government bodies to establish a communications among the individual sensor-equipped vehicles, termed as vehicle-to-vehicle (V2V) communication, and vehicular-to-everything (V2X) communication. Consequently, V2V and V2X can be employed to obtain benefits such as reduction in traffic-related facilities, decrease in logistic cost for vehicular fleet and real-time low-latency reliable communication [1].

Driven by aforementioned motivations and benefits, the standardisation bodies, such as third generation partnership project (3GPP) has proposed a cellular V2X (C-V2X) standard, which aim to realise V2X communication by utilising long term evolution (LTE) technology [2, 3]. In addition, a white paper released by fifth generation (5G) automotive association suggests to employ C-V2X for enhanced road safety and improved connectivity among vehicles [4]. However, the existing C-V2X proposals rely on conventional orthogonal multiple access (OMA), which utilises the available spectrum resources in an orthogonal fashion. As a result, the OMA based C-V2X implementation may not be capable of realising V2X communication under dense traffic environments.

Recently, non-orthogonal multiple access (NOMA) has been proposed as a latest member of multiple access (MA) family and is considered as a promising MA technology for 5G systems. The key idea of NOMA is that it superimposes multiple users into single resource (time/frequency/code) at the transmitter side by allocating different power levels to each user. Successive interference cancellation (SIC) technique is applied at the user receiver to minimize the intra-user interference. The basic principle of NOMA with SIC receiver is that it performs decoding in the ascending order of users' channel gains. Hence, consider a NOMA system with total of M users, where the first user has the lowest channel gain and the last user M has the highest channel gain. Then using SIC, user $1 \leq m \leq M$ decodes all the $m-1$ higher order users before decoding its own message, and treats all the $m+1...M$ lower order users as noise. Some of the key benefits of deploying NOMA include improved spectral efficiency, enhanced throughput and better fairness among users [5]. However, the existing literature is sparse in utilising NOMA for C-V2X communication. In particular, the vehicles approaching road junction have very similar channel conditions with the road side unit (RSU). Consequently, it is challenging to effectively apply NOMA technique for downlink communication between RSU and vehicles at the junction. Therefore, this paper focuses on applying NOMA effectively for V2X under situation of similar channel conditions between vehicles and RSU by proposing two channel gain stretching (CGS) methods.

1.1. Related work, motivation and contributions

The initial investigations on NOMA were conducted in [6] via system level simulations. The authors reported superior throughput and performance of NOMA over conventional OMA scheme. The outage performance of NOMA with randomly deployed users was analytically derived and then evaluated in [7]. The application of multiple input multiple output (MIMO) systems to NOMA was explored in [8]. The authors presented novel design of precoder, which is then utilized to suppress the inter-beam interference. The impact of user pairing on the performance of NOMA system was investigated in [9]. The authors discussed and evaluated the performance of two possible implementations of NOMA systems, namely fixed power allocation NOMA and cognitive-radio-inspired NOMA (CR-NOMA). A NOMA-based device-to-device (D2D) communication was proposed in [10] with underlay cellular network. The concept of group D2D communications was introduced in which D2D transmitter is communicating with multiple D2D receivers via NOMA protocol. In order to manage the interference from underlying uplink cellular communication, an optimal resource allocation strategy was proposed.

More recently, cooperative NOMA was proposed in [11] where strong user is equipped with full-duplex functionality. The authors proposed a scheme to improve the outage performance of a weak user using cooperative and direct transmissions by invoking D2D communications between strong and weak NOMA user pair. A large-scale D2D network was considered in [12], where the authors proposed a cooperative hybrid automatic repeat request assisted NOMA scheme to improve the outage and throughput performance of the D2D users.

The existing literature has paid little attention in investigating NOMA for V2X communications. Some notable contributions in this regard are [13–16]. In [13], low-latency and high-reliable, scheduling and resource allocation algorithms were proposed to realise NOMA based C-V2X communication. The results showed that under the proposed scheduling and resource allocation strategies, the NOMA based C-V2X outperforms its OMA based implementation, particularly under dense network. The problem of dynamic cell association was investigated for NOMA based vehicle-to-small-cell (V2S) communication in [14]. The authors jointly optimised cell association and power allocation to enhance performance and reduce handovers for the considered network. The results showed that the proposed cell association and power allocation scheme outperforms the considered baseline schemes in terms of spectrum efficiency and handover rate. The authors in [15] considered a composite of NOMA and spatial modulation (SM) for V2V massive MIMO system. In order to evaluate the performance, closed-form expressions for bit-error rate are provided. The results affirmed that NOMA-SM has a potential to enhance link reliability and spectrum efficiency for V2V communications. The authors in [16] considered NOMA for V2X communications and exploits side information and physical layer network coding to enhance the decoding reliability in uplink and minimise the transit power requirements in the downlink. The results demonstrated that the NOMA based V2X achieves better performance compared to its OMA based implementation.

In all the aforementioned works, the underlying assumption is to maintain a significant channel gain difference among NOMA users or vehicles (in V2V/V2X) . However, this assumption may not always hold and under those scenarios, it may result in improper rate and power allocation that could result in complete outage [7]. This motivates us to propose a method that artificially generates a channel gain difference among different vehicles to apply NOMA effectively for communication between RSU and vehicles, and hence to obtain proper power allocation under situations of similar channel conditions. To this end, the main contributions of this work are summarized below:

- We propose two CGS schemes to apply NOMA effectively under comparable channel conditions for downlink C-V2X communications.
- In order to evaluate performance, exact expressions for outage probability are derived.
- Numerical results are shown to validate the accuracy of the analysis, as well as compare outage performance of the NOMA for C-V2X under proposed CGS scheme to NOMA based C-V2X without CGS and OMA.

2. System model

Consider a V2X communication scenario as illustrated in Figure 1, where vehicles arriving from different directions converge at the road junction. The RSU is mounted on the traffic pole, as shown in Figure 1, which could be a small cell base station deployed in a dense urban area. Under the considered network scenario, the vehicles approaching to the road junction are located in close proximity of each other. As a result, they have very similar channel conditions with the RSU. For simplicity, we refer to vehicles as *users* in the rest of this paper.

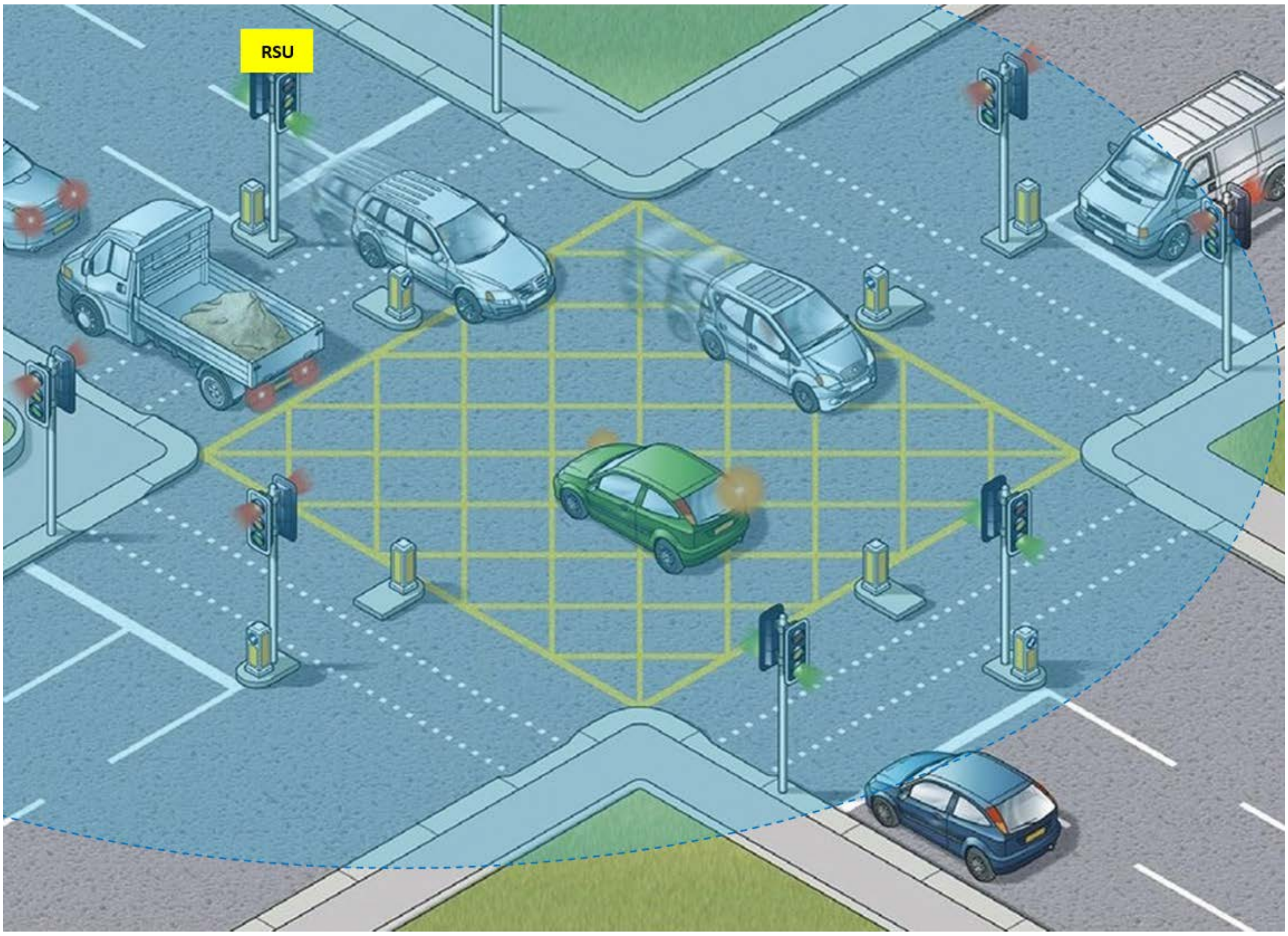

Figure 1. Road junction V2X scenario [17] .

Consider a single-input single-output (SISO) system with single RSU (S) located at the center of a disc D with radius R_D. We focus on a downlink scenario where S is communicating with M users via NOMA protocol. The users are assumed to be randomly uniformly distributed inside disc D. The channel gain between user m and source S is given as, $h_m = g_m d_m^{-\alpha}$, where g_m is the power fading coefficient that follows exponential distribution with unit mean, d_m is the distance between user m and source S and α is the path loss exponent.

Under the considered network setting, all M NOMA users have similar channel conditions i.e., $h_i \approx h_j, i \neq j, 1 \leq i, j \leq M$. It should be noted here that the channel gains of all users are not exactly the same and hence user ordering is still possible. Without loss of generality, the users are ordered as $h_1 \leq ... \leq h_M$. Consequently, the power allocation coefficients, denoted as, $a_m, 1 \leq m \leq M$, and are sorted as, $a_1 \geq ... \geq a_M$. The calculation of power allocation coefficients is discussed in Section 2.1.

2.1. Minimum required power allocation coefficients

Let us denote R_m and $\bar{R}_m$ by achievable and targeted rates of the user m respectively. Then, $\bar{R}_m$ of user m is met if:

$$R_m \geq \bar{R}_m. \tag{1}$$

Equation (1) can be further simplified as:

$$\log_2\left(1 + \frac{Ph_m a_m}{Ph_m \sum_{i=m+1}^{M} a_i + \sigma^2}\right) \geq \bar{R}_m$$
$$a_m \geq \tau_m \left(\sum_{i=m+1}^{M} a_i + \frac{1}{\Upsilon h_m}\right) \tag{2}$$

where $\tau_m = 2^{\bar{R}_m} - 1$, $\Upsilon = \frac{P}{\sigma^2}$ is the transmit signal-to-noise ratio (SNR), P is the maximum transmit power at the RSU and σ^2 is the variance of additive noise. In order to proceed forward, we formulate the following optimization problem to obtain the optimal power allocation coefficients.

$$\min \sum_{m=1}^{M} a_m \tag{3}$$
$$\text{s.t.} \quad (2) \tag{4}$$

To this end, the following lemma states the optimal power allocation coefficients that are sufficient to meet the users' targeted rates.
Lemma: The optimal power allocation coefficient is obtained by solving problem (3) and is given as:

$$a_m = \tau_m \left(\sum_{i=m+1}^{M} a_i + \frac{1}{\Upsilon h_m}\right) \tag{5}$$

Proof. By inspecting problem (3), it can be observed that (3) is convex. Hence, a necessary and sufficient condition to obtain its optimal solution follows by the application of Karush-Kuhn-Tucker (KKT) conditions. The detailed proof follows a standard application of KKT conditions and hence is skipped. Curious reader is referred to see Theorem 1 [18] for the detailed proof. □

3. Proposed channel gain stretching method and outage analysis

In this section, we first propose a CGS method that artificially generates channel gain difference among different NOMA users. Then, under the proposed CGS scheme, we analyse the outage probability of the considered system.

3.1. Channel gain stretching method

CGS Method I

Under situations of similar channel conditions, we propose the following transformation to artificially generate channel gain difference among NOMA users:

$$\bar{h}_m = k_{1,m} (h_m)^{k_{2,m}} \tag{6}$$

where $\bar{h}_m$ is the transformed channel gain of user m and $k_{1,m} > 0, k_{2,m} > 0$ are positive constants for user m and are selected in such a way to achieve a significant difference among channel gains of users.

Example 1: Consider a case of two users with $(h_1, h_2) = (0.87, 0.9)$. Now applying (6) with $k_{1,1} = k_{2,1} = 0.5, k_{1,2} = 3, k_{2,2} = 3.5$ results in stretched coefficients as $\left(\bar{h}_1, \bar{h}_2\right) = (0.46, 2)$. The power allocation coefficients are then computed using (5) for a given SNR and targeted rate.

CGS Method II

The situation of comparable channel conditions for NOMA users is equivalent to the pixels in a digital image having very similar intensities. The visual appearance of the digital image can be enhanced by applying gamma transformation that maps a narrow ambit of intensities into a wider intensity range [19]. Inspired by gamma transformation, a CGS scheme is proposed that maps the channel h_m of the m-th user to a new value, $\bar{h}_m$, which is given as:

$$\bar{h}_m = c_m(h_m + \eta_m)^{\Gamma_m} \tag{7}$$

where c_m , η_m and Γ_m are positive constants, and are selected in such a way to achieve a significant difference among channel gains of the users.

Example 2: Consider that $M = 2$ and $(h_1, h_2) = (0.87, 0.9)$. Now using (7) with $c_1 = 0.5$, $c_2 = 3$, $\eta_1 = \eta_2 = 0.1$, $\Gamma_1 = 1$ and $\Gamma_2 = 0.1$, the stretched channel gains are obtained as $(\bar{h}_1, \bar{h}_2) = (0.485, 3)$. The power allocation coefficients are then computed using (5) for a given SNR and targeted rate.

Note: The parameters $k_{1,m}, k_{2,m}$ and c_m, η_m, Γ_m in (6) and (7), respectively, are decided with an objective to achieve significant difference between channel gains of users, and are obtained after some preliminary experiments. However, it becomes difficult to decide these parameters when the number of users are greater than two. In order to apply the proposed CGS methods efficiently for the case of more than two users, the closed-form expressions or some mechanisms are required to compute these parameters automatically given the original channel gains. As such, these parameters can be found by formulating and solving an optimization problem subject to maintaining a significant difference between channel gains of the users. However, it is beyond the scope of this work and thus is left as a promising direction for future research.

3.2. Outage analysis

Let us consider a CGS method I. The outage occurs at the user m receiver whenever it fails to decode the message signal of any higher order user $j, 1 \leq j \leq m$. Then, the outage probability of user m in decoding user j can be expressed as:

$$\begin{aligned}
P_{m\to j} &= \Pr\left(\frac{\bar{h}_m a_j \Upsilon}{\bar{h}_m \Upsilon \sum_{i=m+1}^{M} a_i + 1} < \tau_j\right) \\
&= \Pr\left[\bar{h}_m \Upsilon \left(a_j - \tau_j \sum_{i=m+1}^{M} a_i\right) < \tau_j\right] \\
&= \Pr\left(\bar{h}_m < \frac{\tau_j}{\Upsilon\left(a_j - \tau_j \sum_{i=m+1}^{M} a_i\right)}\right) \\
&= \Pr\left[h_m < \left(\frac{\varphi_j}{k_{1,m}}\right)^{k_{2,m}}\right]
\end{aligned}$$

$$= F_{h_m}\left(\theta_j\right) \tag{8}$$

where $\varphi_j = \frac{\tau_j}{\Upsilon\left(a_j - \tau_j \sum_{i=m+1}^{M} a_i\right)}$, $\theta_j = \left(\frac{\varphi_j}{k_{1,m}}\right)^{k_{2,m}}$ and F_{h_m} is the cumulative distribution function (CDF) of h_m. Now let us define $\theta_m^{\max} = \max\{\theta_1, ..., \theta_m\}$. The outage probability at user m under CGS method I is then given as:

$$P_m^{\mathrm{I}} = F_{h_m}(\theta_m^{\max}) \tag{9}$$

In order to obtain outage probability P_m of user m, we require CDF of h_m which is obtained by analyzing order statistics [20] and is given as:

$$P_m = \mu_m \sum_{l=0}^{M-m} \binom{M-m}{l} (-1)^l \int_0^{\theta_m^{\max}} \left(F_{\hat{h}}(x)\right)^{m+l-1} f_{\hat{h}}(x) dx \tag{10}$$

where $F_{\hat{h}}$ and $f_{\hat{h}}$ are the CDF and probability density function (PDF) of the unordered channel gain $\hat{h}$ respectively. The CDF $F_{\hat{h}}$ of the unordered channel gain is given as [21]:

$$\begin{aligned} F_{\hat{h}}(x) &= \frac{2}{R_D^2} \int_0^{R_D} \left(1 - e^{-(1+z^\alpha)x}\right) z dz \\ &\overset{(a)}{=} \frac{\delta}{R_D^2} \int_0^{R_D^\alpha} \left(1 - e^{-(1+y)x}\right) y^{\delta-1} dy \\ &\overset{(b)}{=} 1 - \delta e^{-x} \mathrm{B}(1,\delta) \Phi(\delta, 1+\delta; -x R_D^\alpha) \end{aligned} \tag{11}$$

where (a) and (b) are obtained by a change of variable from $z^\alpha \to y$ and applying Eq. 3.383 of [22] respectively, $\delta = \frac{2}{\alpha}$, $\mathrm{B}(\cdot,\cdot)$ is the beta function and $\Phi(\cdot,\cdot;\cdot)$ is the confluent hypergeometric function. Now, take the derivative of (10) to obtain $f_{\hat{h}}$ and substitute $F_{\hat{h}}$ and $f_{\hat{h}}$ in (9), P_m can be expressed as:

$$\begin{aligned} P_m = \mu_m \sum_{l=0}^{M-m} \binom{M-m}{l} (-1)^l \int_0^{\theta_m^{\max}} & \delta \mathrm{B}(1,\delta) e^{-x} \left[\Phi(\delta, 1+\delta; -x R_D^\alpha)\right. \\ & \left. + \rho \Phi(1+\delta, 2+\delta; -x R_D^\alpha)\right] \\ & \times \left[1 - \delta e^{-x} \mathrm{B}(1,\delta) \Phi(\delta, 1+\delta; -x R_D^\alpha)\right]^{m+l-1} dx. \end{aligned} \tag{12}$$

The analytical solution of (12) is difficult to obtain and hence we apply Gaussian-Chebyshev quadrature to approximate the outage probability of user m as follows:

$$\begin{aligned} P_m = \mu_m \sum_{l=0}^{M-m} \binom{M-m}{l} (-1)^l \Bigg\{ \sum_{n=1}^{N} & \Psi_n \left[\Phi(\delta, 1+\delta; -b_n)\right. \\ & \left. + \rho \Phi(1+\delta, 2+\delta; -b_n)\right] \\ \times & \left[1 - \delta e^{-\theta_m^{\max} s_n} \mathrm{B}(1,\delta) \Phi(\delta, 1+\delta; -b_n)\right]^{m+l-1} \Bigg\} \end{aligned} \tag{13}$$

where $b_n = \theta_m^{\max} s_n R_D^\alpha$, $s_n = \frac{1}{2}(1 + \vartheta_n)$, $\vartheta_n = \cos(\frac{2n-1}{2N}\pi)$, $\Psi_n = \delta \omega_n \sqrt{1 - \vartheta_n^2}$ $\mathrm{B}(1,\delta) \theta_m^{\max} e^{-\theta_m^{\max} s_n}$, $\omega_n = \frac{\pi}{N}$ and N is the complexity-accuracy trade-off parameter.

Corollary 8.1. *The outage probability of user m under the application of CGS scheme* II *is given as:*

$$P_m^{\mathrm{II}} = P_m^{\mathrm{I}}|_{\theta_m^{\max} = \bar{\theta}_m^{\max}} \tag{14}$$

where $\bar{\theta}_m^{\max} = \max\left\{\bar{\theta}_1, ..., \bar{\theta}_m\right\}$ and $\bar{\theta}_j = \left(\frac{\varphi_j}{c_m}\right)^{\frac{1}{\Gamma_m}} - \eta_m$.

Proof: In case of CGS method II, the outage at m-th user in decoding any of the higher order user $j, 1 \leq j < m$, is given as, $P_{m\to j} = \Pr\left(\bar{h}_m < \varphi_j\right) = \Pr\left[c_m\left(h_m + \eta_m\right)^{\Gamma_m} < \varphi_j\right] = \Pr\left(h_m < \bar{\theta}_j\right)$. By defining $\bar{\theta}_m^{\max} = \max\left\{\bar{\theta}_1, ..., \bar{\theta}_m\right\}$, the overall outage probability at m-th user under CGS method II is given as, $P_m^{\mathrm{II}} = \Pr\left(h_m < \bar{\theta}_m^{\max}\right)$. Now following the same steps as of (13) proves the result in (14). □

4. Numerical results

This section presents the numerical simulations to validate the accuracy of derived outage results as well as to compare the performance of NOMA system under proposed CGS scheme with no CGS applied and OMA by considering similar channel conditions for all users. In all simulations, we consider $M = 2$, $\bar{R}_1 = \bar{R}_2 = 1$ bits per channel use, $R_D = 20$m, $\Upsilon = [10 - 50]$dB and $N = 5$. Further, as a representative case, the parameters $\left\{h_m, \bar{h}_m, k_{1,m}, k_{2,m}\right\}_{m=1}^{M}$ are taken from Example 1 (section 3.1).

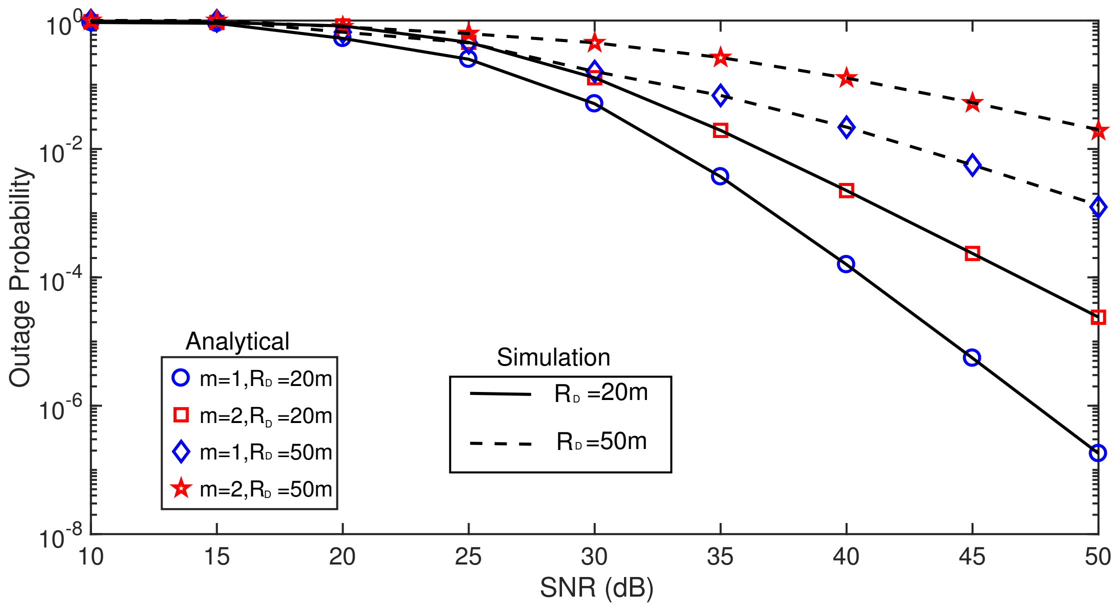

Figure 2. Impact of varying R_D on outage performance.

The impact of varying R_D on the outage performance of the users is presented in Figure 2. Following observations are drawn from the results. First, increasing the radius R_D increases the outage probability of the users due to the higher path loss. Second, user $m = 1$ has lower outage probability than user $m = 2$ because under similar channel conditions scenario, the application of CGS results in $\bar{h}_1 < \bar{h}_2$ (see Example in section 3.1). As a consequence, $a_1 > a_2$ for all SNR values which results in better performance of user $m = 1$. Moreover, Monte-Carlo simulations are also performed to validate the accuracy of derived results in (12). It can be observed that the analytical and simulation results are in good agreement.

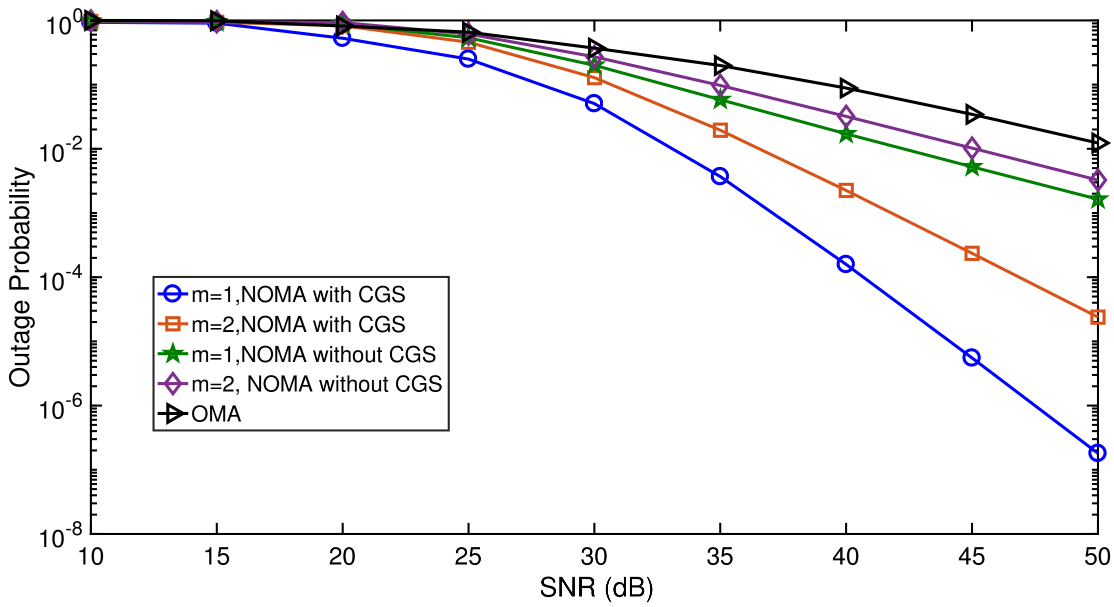

Figure 3. Outage performance comparison among NOMA with and without CGS and OMA under CGS method I.

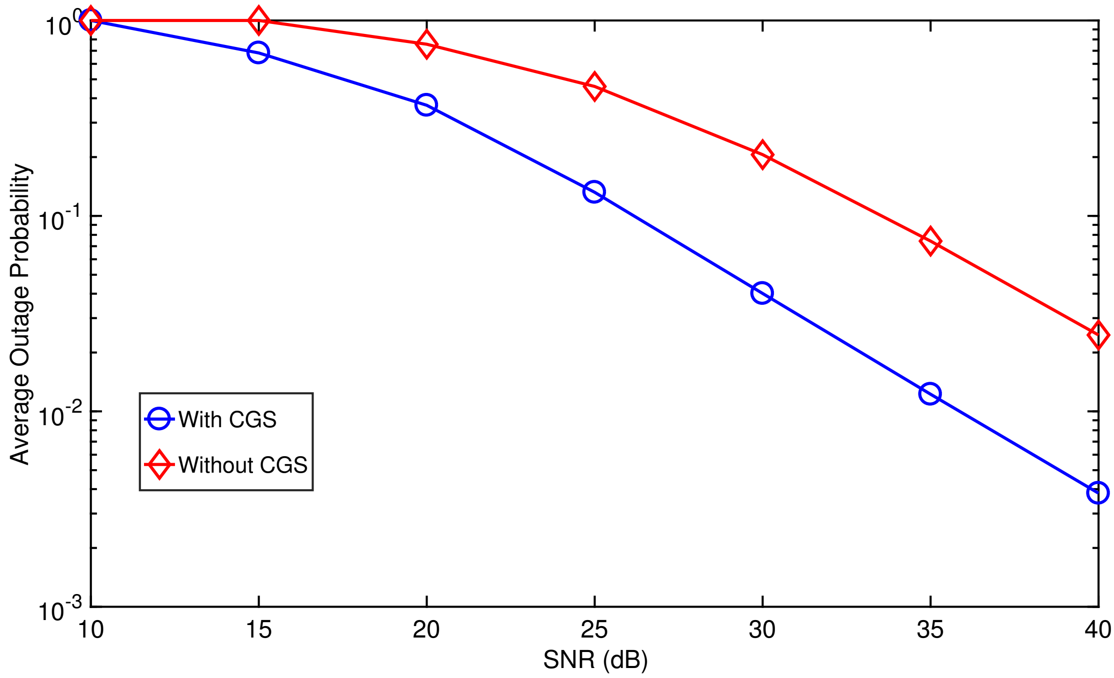

Figure 4. Outage comparison with and without CGS under CGS method II.

The outage performance among NOMA system with CGS, without CGS and OMA is presented in Figure 3. It can be observed that NOMA under proposed CGS scheme outperforms NOMA without CGS and OMA. Further, it can be noted that the performance of NOMA without CGS is badly impacted. These results can be explained as follows: The scenario of similar channel conditions result in very comparable power allocation coefficients, which then increase the signal-to-interference-plus-noise ratio (SINR) threshold required for SIC decoding. By applying proposed CGS using (6) produces significant difference in channel gains resulting in significantly different power allocation coefficients and hence reducing the SINR threshold for SIC decoding. Further, both $m = 1, 2$ users have similar channel conditions, therefore, application of OMA results in same performance for both users, and hence we presented only one result for OMA scheme.

Figure 4 further demonstrate the benefits of applying the proposed CGS method II for users under comparable channel gain parameters as used in Example 2 of Section 3.1. The results show that the average outage performance of users can be enhanced with the proposed CGS method II by $32 - 85\%$ in the considered SNR range. This is because with CGS, users' power allocation coefficients would be computed with significant difference under similar channel conditions, which then results in better SIC operation at users. In addition, by comparing the results in Figures 3 and 4, it can be observed that the CGS method I obtains overall lower outage probability than CGS method II. This is because the CGS method I results in lower SINR threshold $\theta_m^{\max} < \bar{\theta}_m^{\max}$ required for successful decoding.

5. Conclusion

In this work, we consider a scenario of similar channel conditions for NOMA applied to V2X communication. In order to apply NOMA more effectively under these situations, we propose CGS method to artificially generate a channel gain difference among users. Closed-form expression for outage probability is derived to characterize the performance. It can be observed from the results that the NOMA under proposed CGS method outperforms NOMA without CGS and OMA under situations of comparable channel conditions. As future extension of this work, we plan to extend the proposed scheme for MIMO systems.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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