Performance Analysis of NOMA in Vehicular Communications Over i.n.i.d Nakagami-\textit{m} Fading Channels

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Abstract—This paper investigates the performance of non-orthogonal multiple access (NOMA) in vehicular networks where a base station (BS) communicates with the vehicles moving away from the BS with single-input multiple-output. To combine the signals received at the antennas, diversity combining techniques such as maximal ratio combining (MRC) and selection combining (SC) are performed at the receiver of each vehicle. However, in practice, the expected performance from the diversity techniques may not be achieved due to the fact that all the diversity branches are not independent and identically distributed (i.i.d) all the time. In this context, analytical expressions of the outage probability and ergodic sum rate are derived for the considered vehicular networks with the assumption of independent but not necessarily identically distributed (i.n.i.d) Nakagami-\textit{m} fading channels. The performance analysis of NOMA vehicular networks is also extended for multiple-input multiple-output antenna configurations and evaluated in the presence of successive interference cancellation (SIC) error propagation. The obtained analytical results are validated by Monte Carlo simulations. Furthermore, the performance of NOMA is verified with conventional orthogonal multiple access (OMA) for fading parameter \textit{m}=1 and \textit{m}=2 with perfect channel knowledge and channel estimation. Numerical results show that NOMA outperforms the conventional OMA by approximately 20\% and has high sum rate with i.n.i.d as well as i.i.d channel consideration. However, i.n.i.d consideration degrades the performance of NOMA and OMA as the diversity gain achieved with i.n.i.d consideration is less as compared to i.i.d consideration. The performance is further deteriorated with SIC error and channel estimation.

Index Terms—V2I communications, non-orthogonal multiple access, i.n.i.d, outage probability, sum rate.

I. INTRODUCTION

VEHICLE-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications are the essential elements of vehicular communications to reach the goals set by intelligent transport system (ITS) such as driver’s safety, traffic management and infotainment applications [1]. The dissemination of safety messages in V2I and V2V communications demands high reliability [2] and low latency, while the Internet access for traffic management and infotainment applications needs high spectrum efficiency and reliable Internet connectivity. Various infotainment applications such as connected driving and smart transportation will rely on the Internet of Vehicles, which will increase the requirement of spectrum efficiency many folds [3]. However, technologies currently used in vehicular communications such as IEEE 802.11p, long term evolution (LTE), and LTE-Advanced are based on orthogonal multiple access (OMA) and not capable of providing the high bandwidth efficiency and reliability requirements of growing vehicular communications [4].

Non-orthogonal multiple access (NOMA) serves multiple users at the same time or frequency resources by providing multiplexing in the power domain and thus shows significant improvement in spectrum efficiency over OMA [5], [6]. NOMA is an optimistic solution to fulfill the capacity requirements and user access imposed by the multimedia applications and Internet of Things [7]–[9]. NOMA is a promising technique to address the needs of 5G wireless communications such as high spectrum efficiency, massive connectivity and low delay.
NOMA has been used in combination with multiple-input multiple-output (MIMO), cooperative communications, cognitive radio, full-duplex, millimeter-wave, etc. for sum-rate maximization and user fairness in different fading scenarios [6], [12]–[15]. In [13] and [14], the performance of NOMA has been analyzed over Rayleigh fading channels, while [15] considers millimeter-wave channels. The performance of cooperative NOMA for two users scenario has been evaluated in [16] over $\alpha$-$\gamma$-$\kappa$-$\mu$ fading channels. Exact outage performance and the sum rate have been analyzed in cooperative NOMA by considering amplify-and-forward relay over Nakagami-$m$ fading channels [17]. This work was extended in [18] for imperfect CSI. Furthermore, the performance of NOMA has also been evaluated for partial CSI [19]. In [20], the performance of cooperative NOMA has been compared with non-cooperative NOMA in terms of outage probability, system throughput and diversity gain considering Nakagami-$m$ channels. All the above works consider a single input single output (SISO) antenna configuration. In [21], the performance of cooperative NOMA has been studied with antenna selection in downlink MIMO over Nakagami-$m$ fading. Applications of NOMA have been explored in various wireless communication systems such as digital TV, satellite communications, vehicular networks and visible lights communications [22], [23]. In [24], [25], scheduling and resource allocation problems have been addressed in NOMA based vehicular networks to reduce latency and improve reliability. A hierarchical power control algorithm has been proposed in [26] to optimize the power control and cell association jointly for the improvement of spectrum and energy efficiency in NOMA enabled vehicular small cell networks. In [27], the rate performance of NOMA has been compared with OMA for vehicular communications. The works mentioned in [24]–[27] have been carried out for a SISO antenna configuration.

The vehicular network is more heterogeneous as compared to other wireless networks [28]. Reliability of V2I and V2V communications is highly influenced by the mobility of vehicles, line of sight (LOS) and non-line of sight (NLOS) path resulting from static as well as moving obstacles [29]. Diversity combining is a powerful tool to compensate for the performance degradation [30]. In [31], various diversity techniques such as maximal ratio combining (MRC), selection combining (SC) and equal gain combining (EGC) have been exploited to improve the performance of V2I communications by considering independent and identically distributed (i.i.d) diversity links. The energy efficiency of cognitive vehicular networks was optimized with MIMO over i.i.d Rayleigh fading channels [32]. The above works which exploit the diversity to improve the performance of vehicular networks are based on OMA. In [33], massive MIMO technique has been used to exploit the diversity to improve the link reliability and bandwidth efficiency of NOMA embedded vehicular networks over i.i.d channels.

In practice, it is more realistic to assume independent but not identically distributed (i.n.i.d) channels, if the receiver receives the signal with different average power over different channels [34]. Performance of decode-and-forward relaying for wireless networks is evaluated over i.n.i.d Rayleigh fading and Nakagami-$m$ fading channels in [35] and [36]. In practical reality, diversity branches are unbalanced as they experience different path loss or shadowing and contain different noise figures, which result in non-identical fading envelopes of diversity links [37], [38]. Moreover, in vehicular communications, receiver (Rx) antennas mounted on a roof, bumper, or side mirrors of the vehicles may experience shadowing, which may result in different antenna gains over time even for the same type of antennas [39]. In the large vehicle obstruction scenario, the maximum shadowing level experienced at 5.9 GHz frequency is 27 dB for V2V communications and 23 dB and 21 dB in V2I communications for 5m and 7m of roadside unit antenna height [40], [41]. In this case, it is more realistic to assume the channels to be i.n.i.d rather than i.i.d.

All the works carried out in NOMA is with i.i.d channels. Recently, researchers have started on NOMA over i.n.i.d channels. In [42], the outage performance and average achievable rate of NOMA have been evaluated over i.n.i.d Rayleigh fading channels. The outage probability and average throughput have been derived in [43] for various cooperative relaying schemes over i.n.i.d channels. In [44], a scheduling was proposed for a cooperative NOMA system to achieve full diversity and scheduling order simultaneously with i.n.i.d Rayleigh channel consideration. All the works carried out in NOMA with i.n.i.d consideration have been analyzed over Rayleigh fading channels and with a SISO antenna configuration. Performance analysis of NOMA over i.n.i.d Nakagami-$m$ fading channels has not been reported yet.

The aforementioned works carried out in NOMA consider perfect SIC. However, in the case of deep fading scenarios, perfect SIC may not be possible [45]. Therefore, it is more realistic to analyze the performance of vehicular NOMA networks in presence of SIC error propagation. Furthermore, the vehicular channel is estimated using MMSE channel estimator [46].

A. Motivation and Contribution

Infotainment applications such as connected driving and smart transportation are foundations for the future development of ITS. These applications will need connectivity between vehicles and vehicles with sensors and other devices. This connectivity relies on Internet reliability. From the aforementioned survey, NOMA is a promising solution to fulfill the requirements of spectrum efficiency, massive connectivity, and Internet’s reliability. In this article, we consider NOMA based vehicular networks where a base station (BS) communicates with $N$ vehicles over single-input multiple-output (SIMO) and MIMO antenna configurations. The performance is analyzed over Nakagami-$m$ fading channels as it is the most appropriate channel for vehicular communications [47]. As distance between BS and vehicle increases, fading gradually transits from near-Rician to Rayleigh fading. The Receiver performs MRC, SC or singular value decomposition (SVD) to exploit the diversity at the vehicles. However, the diversity gain analyzed under i.i.d assumption is not achieved in practice as the diversity links are non-identical [30] in high fading conditions. Therefore, the i.n.i.d assumption among the diversity branches is more practical for vehicular communications. Although the
The analysis carried out with i.n.i.d assumption increases the analytical complexity, obtained results are more realistic and can be used in the system design of the vehicular networks. Different from the existing work, in this paper, the performance of NOMA enabled vehicular networks is analyzed with i.n.i.d consideration among the diversity branches of Nakagami-$m$ fading channel in presence of SIC error propagation and channel estimation. In particular, the answers to the following core questions comprise the main contributions of this article.

1) **What is the distribution of channel gain for NOMA based vehicular networks?** In this work, closed-form expressions for the cumulative distribution function (CDF) of channel gain of downlink NOMA for V2I communications have been derived over i.n.i.d Nakagami-$m$ fading channels with MRC and SC for Nakagami fading parameter $m = 1$ (Rayleigh fading) and $m = 2$. By considering the i.i.d channels and stationary vehicle ($t = 1$), the CDF is reduced to CDF of NOMA users as in [48]. Further, the CDF is extended for MIMO-NOMA.

2) **How to analyze the performance of NOMA in V2I communications over i.n.i.d and i.i.d channel?** For satisfactory communication, the rate of vehicles should be higher than the target minimum rate. Outage performance of NOMA vehicles is carried out for SIMO-NOMA with MRC and SC diversity combining techniques and MIMO-NOMA over i.n.i.d as well as i.i.d Nakagami-$m$ fading channels at the target minimum rate. From the outage probability in the high SNR regime, diversity order is analyzed. The outage performance is compared with the existing conventional OMA technique, and it has been shown that the performance improvement in NOMA is approximately 20% over OMA. However, i.n.i.d consideration degrades the performance of NOMA as well as OMA. The performance is also observed in the presence of SIC propagation error for MIMO-NOMA.

3) **What is the improvement in spectral efficiency of NOMA based V2I communications over i.i.d and i.n.i.d channels?** Asymptotic analysis of rate and ergodic sum rate of NOMA for V2I communications have been carried out for $1 \times L$ MRC and SC diversity techniques and $K \times L$ MIMO to get the insights in the high SNR regime. The obtained results are compared with conventional OMA. With i.n.i.d consideration, the sum rate is marginally deteriorated. Moreover, the sum rate performance is evaluated with imperfect SIC and channel estimation errors and the impact of velocity is observed.

**B. Paper Organization**

The rest of the article is organized as follows. Section II constitutes the system model and channel model for downlink V2I NOMA networks for single lane scenario. In section III, outage probability and ergodic sum rate of NOMA are derived with the consideration of i.n.i.d Nakagami-$m$ fading channels. Section IV validates the produced analytical expressions using numerical results. Finally, Section V concludes the works followed by references.

**II. SYSTEM MODEL**

We consider downlink V2I communications in a single lane highway vehicular scenario. As shown in Fig. 1, BS situated at roadside communicates with vehicles $U_1, U_2, \ldots, U_N$ moving away from the BS with a similar speed of $v$ km/h [49], [50]. The BS is equipped with $K$ transmit (Tx) antennas while each vehicle is equipped with $L$ Rx antennas. All the diversity links between BS and the vehicles are assumed i.n.i.d as each Rx antenna receives the signal with the different average signal to noise ratio (SNR) due to static and moving obstacles. The fading channels that arise between the BS and vehicles are time selective. According to the autoregressive process, the fading coefficient of the time selective fading channel between the BS and $n^{th}$ vehicle at $t^{th}$ time position can be represented as: [51, Eq.(7)]:

$$H_n(t) = \rho_n^{t-1}H_n(1) + \sqrt{1 - \rho_n^2} \sum_{l=1}^{t-1} \rho_n(t - l - 1)e_n(l)$$ (1)

where $\rho_n = J_0\left(\frac{2\pi L \nu}{R_n C}\right)$ is the correlation parameter for time adjacent channel gain. $v$ is the speed of vehicles, $f_c$ is the carrier frequency, $C$ is the speed of light and $R_n$ represents the transmission symbol rate. $J_0(\cdot)$ defines the zeroth-order Bessel function of the first kind. $e_n(l)$ is time-varying component, which denotes random process distributed as zero-mean circularly symmetric complex Gaussian (ZM-CSCG) with variance $\sigma_e^2$. $H_n(1)$ is small scale fading channel affected by path loss $\epsilon$, can be represented as a function of distance $d_n$ between the BS and $n^{th}$ vehicle at $t = 1$, $H_n(1) = \frac{H_{dn}(1)}{\sqrt{1 + d_n^\epsilon}}$, where $H_{dn}(1)$ represents Nakagami-$m$ channel between the BS and $n^{th}$ vehicle. Without loss of generality, the channels from BS to $N$ vehicles at $t = 1$ time instant are ordered as $|H_1(1)|^2 \leq |H_2(1)|^2 \leq \ldots \leq |H_N(1)|^2$. NOMA is employed at the BS to associate the signals for multiple vehicles in the power domain using superposition coding. Power coefficients allocated to vehicles are $\alpha_1(t) \geq \alpha_2(t) \geq \ldots \geq \alpha_N(t)$ considering the channel order $|H_1(t)|^2 \leq |H_2(t)|^2 \leq \ldots \leq |H_N(t)|^2$.
at \(t^{th}\) time instant. The signal received by the \(n^{th}\) vehicle at \(t^{th}\) timing instant is observed as:

\[
y_n(t) = H_n(t) \sum_{i=1}^{N} \sqrt{P_s} \alpha_i(t) s_i(t) + \eta_n(t),
\]

where \(\eta_n(t)\) is \(L \times 1\) additive white Gaussian noise vector with zero mean and variance \(\sigma^2\), \(s_i\) represents \(K \times 1\) message signal vector of \(j^{th}\) vehicle, \(P_s\) is transmission power. SNR received at the vehicle changes with mobility. The altered SNR at the \(n^{th}\) vehicle can be written as [51, Eq.(12)]:

\[
\zeta_v = \left[ \frac{1}{\zeta} \left( 1 - \frac{\beta^2}{\rho} \right) \sigma^2 \right]^{-1},
\]

where \(\zeta\) denotes the SNR from the BS. The received Signal to Interference plus Noise Ratio (SINR) at NOMA vehicles is shown below.

\[\psi_{j,n} = \frac{\alpha_j(t) \zeta_v |H_n(t)|^2}{\zeta_v |H_n(t)|^2 + \alpha_j(t) + 1},\]

where \(\alpha_j(t) = \sum_{i=j+1}^{N} \alpha_i(t)\). The SINR derived in (4) assumes the perfect decoding, reconstruction and subtraction of all \(n - 1\) vehicles’ signal during SIC at the \(n^{th}\) vehicle. This is an unrealistic assumption for vehicular networks. Assuming that the SIC of \(n - 1\) vehicles is not perfect at the \(n^{th}\) vehicle, there will be residues of signal power from \(n - 1\) vehicles during decoding of its own signal. With imperfect SIC, the SINR of NOMA vehicles can be modified as:

\[
\tilde{\psi}_{j,n} = \frac{\alpha_j(t) \zeta_v |H_n(t)|^2}{\zeta_v |H_n(t)|^2 + \alpha_j(t) + 1},
\]

where \(\tilde{\alpha}_j(t) = \sum_{i=j+1}^{N} \alpha_i(t) \beta_i\) and \(0 \leq \beta \leq 1\) is the error propagation factor which is inversely proportional to the SINR represented in (4) [45]. \(\beta = 0\) represents perfect decoding and the SINR of (5) becomes (4), while \(\beta = 1\) is the worst case where the entire signal is considered as interference. SINC of the \(N^{th}\) vehicle with SIC residual, while decoding it’s own signal is:

\[
\psi_{n,N} = \frac{\alpha_N(t) \zeta_v |H_n(t)|^2}{\zeta_v |H_n(t)|^2 + \beta_j(t) + 1},
\]

In order to compare NOMA with OMA, the SINR of the \(n^{th}\) vehicle of OMA can be shown as:

\[
\psi_{n,OMA} = \frac{a_n \zeta_v |H_n(t)|^2}{b_n},
\]

where \(a_n\) is a power coefficient and \(b_n\) is a parameter of resource, related to the \(n^{th}\) vehicle of OMA. For one of the OMA techniques, frequency division multiple access, \(b_n = \frac{1}{N}\).

B. Sum Rate of NOMA Vehicles

The achievable rate of the \(n^{th}\) vehicle for NOMA V2I communications can be represented as:

\[
R_n = \log(1 + \psi_{n,n})
\]

\[= \log \left( 1 + \frac{\alpha_n(t) \zeta_v |H_n(t)|^2}{\zeta_v |H_n(t)|^2 (\alpha_n(t) + \beta_n(t)) + 1} \right),\]

where \(\psi_{n,n}\) is the SINR of the \(n^{th}\) vehicle to detect its own signal. The sum rate of downlink NOMA can be written as:

\[
R_{sum} = \sum_{n=1}^{N} \log(1 + \psi_{n,n})
\]

\[= \sum_{n=1}^{N} \log \left( 1 + \frac{\alpha_n(t) \zeta_v |H_n(t)|^2}{\zeta_v |H_n(t)|^2 (\alpha_n(t) + \beta_n(t)) + 1} \right) + \log \left( 1 + \frac{\alpha_N(t) \zeta_v |H_N(t)|^2}{\zeta_v |H_N(t)|^2 \beta_N(t) + 1} \right),\]

C. Density Functions and Statistics of Channel Gain for SIMO-NOMA Systems

The performance of NOMA based vehicular networks is analyzed under Nakagami-\(m\) fading. Channel gain between the BS and \(l^{th}\) antenna of the \(n^{th}\) vehicle is denoted as \(h_{nl}\). The probability density function (PDF) of instantaneous received SNR can be written as [52],

\[f_{|h_{nl}|^2}(x) = \frac{\lambda_{ill}^{m_l}}{\Gamma(m_l)} x^{m_l - 1} e^{-\lambda_{ll}x},\]

where \(\lambda_{ll} = \frac{m_l}{\Omega_l}\), \(m_l \geq \frac{1}{2}\) and \(\Omega_l = E \left[ |h_{nl}|^2 \right]\) are shape and scale parameters of Nakagami-\(m\) fading. We assume equal fading parameters of all the links, \(m_1 = m_2 = \ldots = m_L = m\), and the average received SNR of various diversity links are separated with exponential power decay profile. The average received SNR of \(l^{th}\) diversity link is represented as \(\Omega_l = \Omega_\delta e^{-(l-1)\delta}\), where \(\Omega_\delta\) is the maximum received average SNR and \(\delta\) is the decaying factor [53]. For i.i.d consideration, the power decay factor \(\delta = 0\), and \(\Omega_1 = \Omega_2 = \Omega_L\) which leads to \(\lambda = \lambda_1 = \lambda_2 = \ldots = \lambda_L\). By integrating (10) with the aid of [54, Eq.(8.350.2)], the CDF of the instantaneous received SNR can be obtained as:

\[F_{|h_{nl}|^2}(x) = \frac{\Gamma(m_{\lambda})}{\Gamma(m)},\]

where \(\Gamma(\cdot,\cdot)\) is upper incomplete Gamma function and \(\Gamma(\cdot)\) [54, Eq.(8.310.1)] is the Gamma function.
1) Maximal Ratio Combining: The signals received over $L$ Rx antennas mounted on each vehicle are combined using MRC. We consider that all the diversity links are i.n.i.d. The channel coefficients of 1, 2, …, $L$ links of the $n$th vehicle are denoted as $|h_{n1}(t)|$, $|h_{n2}(t)|$, …, $|h_{nL}(t)|$. An unordered channel gain at the $n$th vehicle with MRC over i.n.i.d diversity links can be expressed as:

$$\| \hat{h}_n(t) \|^2_{\text{MRC}} = \sum_{l=1}^{L} |h_{nl}(t)|^2, l = 1, 2, \ldots, L$$  \hspace{1cm} (12)

The CDF of an unordered channel gain of $L$ i.n.i.d branches can be obtained by finding inverse Laplace transform of MGF of $L$ links. The MGF of the $l^{th}$ link is calculated as:

$$MGF_l(s) = \int_0^\infty e^{-sx} f_{|h_{nl}|^2}(x) dx = \lambda_l^m (s + \lambda_l)^{-m}$$  \hspace{1cm} (13)

Since all the links are independent, the MGF of the $L$ i.n.i.d branches with MRC can be obtained by multiplying MGF of the $L$ diversity links. With the help of (13), MGF of the $n$th vehicle with MRC can be written as:

$$MGF_{M,n}(s) = \prod_{l=1}^{L} MGF_l(s)$$  \hspace{1cm} (14)

From MGF, the CDF of an unordered channel gain at the $n$th vehicle can be calculated as:

$$F_{M,n,\|h_n\|^2}(x) = L^{-1} \left\{ \frac{1}{s} \prod_{l=1}^{L} \left( \frac{\lambda_l^m (s + \lambda_l)^{-m}}{s} \right) \right\}$$  \hspace{1cm} (15)

By solving (15), the CDF of an unordered channel gain for $L$ independent links for $m \in [1, 2]$ can be obtained as (16), shown at the bottom of the next page.

The CDF of an ordered channel gain of MRC in (16) represents the sum of Gamma variates of $m$ independent links which can be obtained by mathematical induction for various values of $L$ and $m = 1, 2$. Further, from [17, Eq.(19)], the CDF of an ordered channel gain of NOMA can be written as:

$$F_{n,\|h_n\|^2}(x) = \frac{N!}{(N-n)! (n-1)!} \sum_{j=0}^{N-n} \frac{(-1)^j}{n+j} \binom{N-n}{j} \times \left( F_{\|h_n\|^2}(x) \right)^{n+j}$$  \hspace{1cm} (17)

where $F_{\|h_n\|^2}(x)$ is an unordered channel gain at the $n$th vehicle. Now by applying (16) into (17), the CDF of an ordered channel gain of NOMA vehicles is obtained in Lemma 1.

**Lemma 1:** When $m \in [1, 2]$ and $L \in \mathbb{Z}$, the CDF of ordered channel gain of i.n.i.d Nakagami-$m$ fading channels for MRC can be expressed as:

$$F_{M,n,\|h_n\|^2}(x) = \frac{N!}{(N-n)! (n-1)!} \sum_{j=0}^{N-n} \frac{(-1)^j}{n+j} \binom{N-n}{j} \times \left( \frac{1}{s} \prod_{l=1}^{L} \left( \frac{\lambda_l^m (s + \lambda_l)^{-m}}{s} \right) \right)^{n+j} \times \left( \prod_{l=1}^{L} \left( \frac{1}{s} \prod_{j=0}^{m} \left( \frac{1}{s} \right) \right) \right)^{n+j}$$  \hspace{1cm} (18)

**Proof:** Please refer to Appendix I. \hspace{1cm} $\blacksquare$

2) Selection Combining: Though MRC is an optimal diversity combining technique in terms of performance gain, it has high complexity, while the implementation of SC is simple [56]. So, we analyze the performance with SC technique to compare it with MRC. An unordered channel gain of the $n$th vehicle with SC of $L$ i.n.i.d links can be written as:

$$\| \tilde{h}_n(t) \|^2_{\text{SC}} = \max_{l=1, 2, \ldots, L} |h_{nl}(t)|^2$$  \hspace{1cm} (19)

From (11), the CDF of an unordered channel gain of the $n$th vehicle with $1 \times L$ SC over i.n.i.d channels can be written as [53, Eq.(22)]:

$$F_{SC,\|\tilde{h}_n\|^2}(x) = \prod_{l=1}^{L} \frac{\Gamma(m, \lambda_l x)}{\Gamma(m)} = \prod_{l=1}^{L} \left[ 1 - e^{-\lambda_l x} \left( \sum_{i=0}^{m} \frac{1}{i!} (\lambda_l x)^i \right) \right]$$  \hspace{1cm} (20)

By substituting (20) into (17), the CDF of an ordered channel gain of SC NOMA is derived as:

$$F_{SC,\|h_n\|^2}(x) = \frac{N!}{(N-n)! (n-1)!} \sum_{j=0}^{N-n} \frac{(-1)^j}{n+j} \binom{N-n}{j} \times \left( \prod_{l=1}^{L} \left[ 1 - e^{-\lambda_l x} \left( \sum_{i=0}^{m} \frac{1}{i!} (\lambda_l x)^i \right) \right] \right)^{n+j}$$  \hspace{1cm} (21)

The ordered CDF of SC-NOMA can be simplified using multinomial theorem as shown in Appendix I.

In case of high fading severity due to high velocity, the PDF of the received SNR can be derived as follows. For simplicity we consider SISO antenna configuration. By substituting (3) into (10), the PDF of SNR for high fading scenario can be obtained in (25). By substituting $n_1 = 1$ and integrating (25), the CDF can be obtained in (26).

**D. MIMO-NOMA Systems**

This section describes NOMA enabled downlink V2I communications where the BS is equipped with $K$ antennas while
each vehicle is equipped with $L$ antennas. The channel matrix between BS and vehicle can be written as:

$$H_n(t) = \begin{bmatrix} h_{n11}(t) & \cdots & h_{n1K}(t) \\ \vdots & \ddots & \vdots \\ h_{nL1}(t) & \cdots & h_{nLK}(t) \end{bmatrix}$$  \hspace{1cm} (22)$$

The channel matrix for MIMO can be represented using SVD as: 

$$\| H_n(t) \|^2 = \text{Tr} \left[ H_n(t) H_n(t)^H \right] = U \Lambda^* U^*$$ \hspace{1cm} (23)$$
where $U \in \mathbb{C}^{L \times L}$, $V \in \mathbb{C}^{K \times K}$ are unitary matrices and $\Lambda \in \mathbb{R}^{L \times K}$ is a rectangular matrix whose diagonal elements are non-negative real numbers and off-diagonal elements are zero. In $K \times L$ MIMO, the signal from each Tx antenna is transmitted over $L$ diversity links. Therefore, the CDFs of the unordered channel gain and ordered channel gain of MIMO-NOMA are same as those of MRC derived in (16) and (18) respectively.

### E. Channel Estimation

In vehicular networks, the availability of perfect CSI is not a valid assumption all the time. Therefore, the vehicular channel is estimated with a minimum mean square error (MMSE) channel estimator. The MMSE-estimated channel of the $n^{th}$ vehicle, estimated with MMSE estimation is:

$$H_n(t) = \left[ P_{\text{train}}^H R_n^{-1} P_{\text{train}} + R_h_n^{-1} P_{\text{train}}^H R_n^{-1} Y_n(t) \right]$$ \hspace{1cm} (24)$$

where $P_{\text{train}}$ is training sequence, $R_n$ is a noise variance and $R_h_n$ is a channel variance.

### III. Performance Analysis of SIMO and MIMO-NOMA for Vehicular Communications

In this section, outage performance and rate of the NOMA vehicles have been derived over i.n.i.d Nakagami-$m$ fading channel with $1 \times L$ MRC, SC and $K \times L$ MIMO techniques. Further, to get more insights, diversity gain is discussed.

#### A. Outage Performance of V2I NOMA:

The outage probability characterizes the probability of the $n^{th}$ vehicle that the $j^{th}$ vehicle cannot decode the $j^{th}$ vehicle’s signal, $1 \leq j \leq n$ as the rate of the $n^{th}$ vehicle to detect the $j^{th}$ vehicle is less than the target minimum rate $R_{ij}$. The outage probability of $n^{th}$ vehicle can be defined as:

$$P_{out,n} = 1 - Pr(\psi_{1,n} > \psi_{nh,1}) \cap (\psi_{2,n} > \psi_{nh,2}) \cap \cdots \cap (\psi_{n,n} > \psi_{nh,n})$$ \hspace{1cm} (29)$$

where $\psi_{ij,n} = \frac{\zeta \alpha_j(t) h_{ij,n}(t)^2}{\zeta \| h_{ij,n}(t) \|^2 (\alpha_j(t) + \beta_j(t)) + 1}.$

$$P_{out,n} = 1 - Pr\left( (\| h_1(t) \|^2 > \phi_1) \cap \cdots \cap (\| h_n(t) \|^2 > \phi_n) \right) = 1 - Pr(\| h_n(t) \|^2 > \phi_{mn})$$ \hspace{1cm} (30)$$

where $\phi_{mn} = \max(\phi_1, \phi_2, \ldots, \phi_n)$ and $\phi_j = \frac{\zeta \alpha_j(t) \psi_{ij,j} (\alpha_j(t) + \beta_j(t))}{\zeta \| h_{ij,n}(t) \|^2}$, where $\psi_{ij,j} = 2^{R_{ij}^{-1}}$ represents the threshold SNR for detecting the $j^{th}$ vehicle’s signal with the target minimum rate of $R_{ij}$ under the condition $\alpha_j(t) > \psi_{ij,j} (\alpha_j(t) + \beta_j(t))$. $F_{\| h_{ij,n}(t) \|^2}(x)$ is the CDF of an ordered channel gain of the $n^{th}$ vehicle of NOMA. With the help of (18), the outage probability of the $n^{th}$ vehicle of MRC-NOMA over i.n.i.d Nakagami-$m$ channels can be obtained as (27).

Similarly using (21), the outage probability of NOMA vehicles with SC over i.n.i.d Nakagami-$m$ channel can be acquired as:

$$P_{out,SC,n} = \frac{N!}{(N-n)! (n-1)!} \sum_{j=0}^{N-n} (-1)^j \binom{N-n}{j} \times \left( \prod_{l=1}^{L} \left[ 1 - e^{-\lambda \phi_{mn}} \left( \frac{\sum_{j=0}^{n-1} \lambda_l \phi_{mn}^j}{\lambda_l \phi_{mn}} \right)^{n-j} \right] \right)$$ \hspace{1cm} (31)$$

From (26), the outage probability of NOMA vehicles in severe fading condition can be obtained in (28). The outage probability of MIMO-NOMA is the same as MRC-NOMA derived in (27).

#### B. Diversity Gain Analysis

In this section, the diversity order of vehicles for NOMA enabled vehicular communications with multiple antenna configurations is discussed. The diversity order is defined as:

$$\lim_{\zeta \to \infty} \frac{\log(P_{out}(\zeta))}{\log(\zeta)}$$ \hspace{1cm} (32)$$

where

$$A_{w_0} = \frac{\sum_{p=1}^{L} \left( -1 \right)^{p-1} \left( \sum_{w_1=1, \ldots, \sum_{w_1=1, \ldots, w_1}^L \lambda_{w_0} \lambda_{w_1}^{p-1} \prod_{w_1=1, \ldots, w_1}^L \lambda_{w_1}^{m-1} \right)}{\prod_{w_1=1, \ldots, w_1}^L \lambda_{w_1}^{m-1} \left( \lambda_{w_0} - \lambda_{w_1} \right)^2 m - 1}$$

$$B_{w_0} = \frac{\prod_{w_1=1, \ldots, w_1}^L \lambda_{w_1}^{-1} \left( \lambda_{w_0} - \lambda_{w_1} \right)^2 m - 3}$$
For i.i.d diversity links, we apply \( \lambda = \lambda_1 = \lambda_2 = \ldots = \lambda_L \) in (15). The CDF of an unordered channel gain over \( L \) i.i.d links can be simplified as:

\[
F_{M,n,\|h_n\|^2}(x) = \frac{x^{Lm} \lambda^{Lm} (Lm)!}{\Gamma(Lm) \Gamma(Lm, \lambda x)}
\]

(33)

By substituting (33) into (17), the CDF of an ordered channel gain can be obtained. By applying the obtained CDF into (30), with the aid of [17], the outage probability in the high SNR regime \( \zeta \to \infty \) so, \( \phi_{mn} \to 0 \) can be written as:

\[
F_{M,n,\|h_n\|^2}(x) \approx \frac{N!}{(N-n)!(n)!} (\phi_{mn} \lambda)^{Lm} m^n
\]

(34)

By inserting (34) into (32), the obtained diversity order is \( L \) terms with non-identical links is always less than the i.i.d case. Hence, the diversity order is the same as i.n.i.d. MRC-NOMA.

Remark 1: Although the diversity gains of MRC-NOMA and SC-NOMA are the same, from (12) and (19), the performance improvement in average SNR with an increase in the number of Rx antennas is higher in MRC-NOMA as compared to SC-NOMA. Further, the diversity order of MIMO-NOMA is the same as that of MRC-NOMA.

C. Ergodic Sum Rate of V2I NOMA

The ergodic sum rate is a measure of spectrum efficiency. Sum rate of \( N \) vehicles for NOMA over i.i.d Nakagami-\( m \) fading channel is:

\[
R_{sum} = \sum_{n=1}^{N} \int_{0}^{\infty} \log \left( 1 + \frac{\alpha_n(t) \zeta_v}{\zeta_v \| h_n(t) \|^2 \sigma_n(t) + 1} \right) f_{M,n,\|h_n\|^2}(x) dx + \int_{0}^{\infty} \log \left( 1 + \frac{\alpha_N(t) \zeta_v}{\zeta_v \| h_N(t) \|^2 \sigma_N(t) + 1} \right) f_{M,n,\|h_n\|^2}(x) dx = R_{N-1} + R_N
\]

(35)

From [57, eq.(14)], ergodic sum rate of \( N \) vehicles for SIMO-NOMA is:

\[
R_{sum} = \sum_{n=1}^{N-1} \int_{0}^{\infty} \log \left( 1 + \frac{\alpha_n(t) \zeta_v}{(\alpha_n(t) + \beta_n(t)) \zeta_v + 1} \right) f_{M,n,\|h_n\|^2}(x) dx + \int_{0}^{\infty} \log \left( 1 + \frac{\alpha_N(t) \zeta_v}{\zeta_v \| h_N(t) \|^2 \sigma_N(t) + 1} \right) f_{M,n,\|h_n\|^2}(x) dx = R_{N-1} + R_N
\]

(36)
Hence, for simplicity, we analyze the asymptotic behaviour of the ergodic sum rate at SNR, $\zeta_v \to \infty$.

1) Asymptotic Analysis With Imperfect SIC: Sum rate in the presence of SIC error propagation at $\zeta_v \to \infty$ can be approximated as:

$$R_{\text{sum},\infty} = \sum_{n=1}^{N-1} \log \left( 1 + \frac{\alpha_n(t)}{\alpha_n(t)} \right) + \log \left( 1 + \frac{\alpha_N(t)}{\beta_N(t)} \right)$$

(37)

The sum rate with SIC error propagation is constant and depends on the error propagation factor.

2) Asymptotic Analysis With Perfect SIC: Sum rate of first N-1 vehicles at $\zeta_v \to \infty$ can be approximated as:

$$R_{N-1,\infty} = \sum_{n=1}^{N-1} \log \left( 1 + \frac{\alpha_n(t)}{\alpha_n(t)} \right)$$

(38)

Now, with the help of identity

$$\int_0^{\infty} \ln(1 + \sigma z) f(z) dz = \sigma \int_0^{\infty} \frac{1 - F(z)}{1 + \sigma z} dz,$$

$R_{N,\infty}$ can be written as:

$$R_{N,\infty} = \frac{\alpha_N(t)\zeta_v}{\ln 2} \int_0^{\infty} \frac{1 - F_n(x)}{1 + \alpha_N(t)x} \zeta_v dx$$

(39)

Expression of the rate of the $N^{th}$ vehicle at $\zeta_v \to \infty$ is obtained in Lemma 2.

By applying (38) and (40) into (36), the ergodic sum rate of the $N$ vehicles of NOMA can be obtained as (44).

$$R_{\text{sum},M,\infty} \approx \sum_{n=1}^{N-1} \log \left( 1 + \frac{\alpha_n(t)}{\alpha_n(t)} \right) + \frac{\alpha_N(t)\zeta_v}{\ln 2} \sum_{i=1}^{k} G_i u_i,$$

(44)

where $G_i$ is multiplier constant of $u_i$ and $k = \left( \frac{N+mL}{N} \right)$ is number of terms resulting from the multinomial theorem.

By applying $n = N$ and (20) into (39), the rate of the $N^{th}$ vehicle of SC-NOMA can be written as (45), which is simplified with the help of a multinomial theorem as described above in Lemma 2. The sum rate of vehicles with SC can be written as (46).

IV. RESULTS AND DISCUSSION

This section presents simulation results to validate analytical expressions of the outage probability and sum rate for NOMA based vehicular networks. We consider V2I downlink single lane scenario where vehicles $U_1$, $U_2$ and $U_3$ are moving away from the BS with the speed $v = 55$ km/h. The BS communicates with vehicles $U_1$, $U_2$ and $U_3$ with the transmission symbol rate of $R_s = 10$ Mbps and the carrier frequency $f_c = 5.9$ GHz. $U_1$ is the farthest vehicle from BS and experiences the worst channel condition, while $U_3$, which is the nearest vehicle undergoes the best channel as the channel condition is inversely proportional to distance as per $H_n(1) = \frac{1}{d_n^\epsilon}$, where path loss exponent $\epsilon = 3$.

The power coefficients $\alpha_1(1)$, $\alpha_2(1)$ and $\alpha_3(1)$ allocated to vehicles $U_1$, $U_2$ and $U_3$ are 0.6, 0.27 and 0.13 at $t = 1$. At $t^{th}$ instant, the order of the power coefficients is rearranged as per the channel order of the vehicles at that time instant. The target minimum rate for detection of each vehicle is $R_t = 1$ bps/Hz, which results into threshold SNR $\psi_{th,1} = \psi_{th,2} = \psi_{th,3} = 1$ for NOMA vehicles. The threshold SNR for conventional OMA is $\psi_{th} = 7$ which can be found from $\frac{1}{3} \sum_{n=1}^{N} \log_2 (1 + \psi_{th,n}) = \frac{1}{4} \log_2 (1 + \psi_{th})$. Autoregression of the vehicular channel is carried out at time position $t = 3$ with $\sigma_{en}^2 = 0.01$. The receiver at each vehicle combines the received signals using MRC and SC techniques for SIMO-NOMA and SVD for MIMO-NOMA.

where $\lambda_{en}$ and $q$ are constants. By approximating (45) using (50) and applying (38) and (45) into (36), the ergodic sum rate of vehicles of SC-NOMA over i.i.d Nakagami-$m$ is obtained as:

$$R_{\text{sum},SC,\infty} \approx \sum_{n=1}^{N-1} \log \left( 1 + \frac{\alpha_n(t)}{\alpha_n(t)} \right) + \frac{\alpha_N(t)\zeta_v}{\ln 2} \sum_{i=1}^{k} \Theta_i u_i,$$

(46)

where $\Theta_i$ is multiplier constant of $u_i$ and $k = \left( \frac{N+(m+1)^{k-1}}{N} \right)$.

All the diversity branches at each vehicle are assumed i.i.d, and hence the average SNR received at each link is separated with exponential power decay profile. For simulation, we consider the maximum received average SNR is $\Omega_1 = 3$ and decaying factor $\delta = 0.3$. The results obtained with i.i.d consideration are compared with i.i.d channel consideration by assuming perfect channel knowledge.

Fig. 2(a) shows the outage performance of three vehicles of NOMA and a conventional OMA for $m = 1$, which represents the Rayleigh fading channel (NLOS condition). The results show that the outage performance of the vehicle with the best channel condition ($U_3$) outperforms among all three vehicles even though it is served with the lowest power coefficient from the BS. A vehicle with the worst channel condition ($U_1$) performs poorly as compared to $U_2$ and $U_3$ while it
outperforms conventional OMA because it is served with high power coefficient in NOMA compared to OMA.

Fig. 2(b) shows the outage performance of the vehicles with NOMA and OMA with \( m = 2 \). The performance is improved as compared to \( m = 1 \) as the diversity gain is higher for \( m = 2 \). For \( m = 2 \), \( U_1 \) of NOMA performs 1.6 dB better than OMA. However, the performance degradation due to i.n.i.d consideration is higher in case of \( m = 2 \) as compared to \( m = 1 \). It means the effect of i.n.i.d consideration is less in NLOS conditions.

The outage performance of \( 1 \times 2 \) and \( 1 \times 4 \) MRC-NOMA and OMA are presented in Fig. 3(a) and Fig. 3(b) for \( m = 1 \). It is observed that the performance degradation because of i.n.i.d assumption is the lowest for a vehicle with the worst channel condition and the degradation increases as the channel condition gets stronger. Deterioration effect due to i.n.i.d assumption is higher in \( 1 \times 4 \) as compared to \( 1 \times 2 \). It is observed that the diversity loss due to i.n.i.d consideration, increases with an increase in the number of Rx antennas.

Fig. 4(a) and Fig. 4(b) express the outage performance of \( 1 \times 2 \) and \( 1 \times 4 \) MRC-NOMA and OMA for \( m = 2 \). For \( 1 \times 2 \) and \( 1 \times 4 \), the outage performance is improved in case of \( m = 2 \) as compared to \( m = 1 \) as fading severity is higher in case of \( m = 1 \). It is worth mentioning that at the outage probability less than \( 10^{-3} \), simulation results deviate from the analytical results due to practical limitation of sample sizes used in simulations due to insufficient computer memory.

Baring this limitation, the simulation results generally provide adequate accuracy and are sufficient to validate the correctness of the analytical results obtained in this work.

Fig. 5(a) and 5(b) express the outage performance of \( 1 \times 2 \) and \( 1 \times 4 \) SC-NOMA and OMA for \( m = 1 \). The outage performance is deteriorated by 2 dB for \( 1 \times 2 \) and 3 dB for \( 1 \times 4 \) as compared to MRC. Fig. 6(a) and 6(b) show the outage performance with SC-NOMA for \( m = 2 \). The performance degradation with i.n.i.d channel consideration is same as MRC for \( m = 1 \). However, the performance improvement in NOMA with respect to OMA is maintained the same as MRC and the loss due to i.n.i.d assumption is maintained the same for both the values of \( m \).

Fig. 7 shows analytical performance of \( U_1 \), \( U_2 \) and \( U_3 \) in high fading condition for \( v = 55 \) and \( v = 120 \) km/hour. The performance degradation due to increase in velocity is highest for \( U_3 \) while lowest for \( U_1 \).

Fig. 8 presents the outage performance of \( 2 \times 2 \) and \( 4 \times 4 \) MIMO-NOMA with SIC residual error. The results show the effect of SIC residual error on vehicles \( U_2 \) and \( U_3 \). Vehicle \( U_1 \) is not shown as it is decoded first and not suffered from any residue. Vehicle \( U_2 \) is affected by the residue of \( U_1 \), while

---

Lemma 2: For high SNR approximation and \( m \in [1, 2] \), \( L \in \mathbb{Z} \), the rate of the \( N^{th} \) vehicle for \( L \) diversity links is obtained as:

\[
R_{N,M,\infty} = \frac{\alpha N(t) \zeta_v}{\ln 2} \int_0^\infty \left\{ \sum_{b_1+b_2+\ldots+b_{mL+1}=L} \left( b_1, b_2, \ldots, b_{mL+1} \right) \prod_{w_0=1}^{mL+1} \left( C_{w_0} x^q e^{-\lambda_{w_0} x} \right)^{b_{w_0}} \right\} + 1 \int dx,
\]

where \( \left( b_1, b_2, \ldots, b_{mL+1} \right) = \frac{\prod_{k=1}^{mL+1} x^q e^{-\lambda_{w_0} x}}{b_1 b_2 \ldots b_{mL+1} x^m} \) are multinomial coefficients [58] and \( C_{w_0} \) and \( q \) are constants. By using approximation of (50) as shown in Appendix II, the rate of the \( N^{th} \) vehicle can be written as:

\[
R_{N,M,\infty} \approx \frac{\alpha N(t) \zeta_v}{\ln 2} \sum_{i=1}^k G_{iL} u_i
\]

Proof: By taking \( n = N \) in (17) and applying it into (39), the rate of the \( N^{th} \) vehicle can be written as:

\[
R_{N,M,\infty} = \frac{\alpha N(t) \zeta_v}{\ln 2} \int_0^\infty \frac{1 - (F_{M,n,\left\| h_0 \right\|}(x))^N}{1 + \alpha N(t) x \zeta_v} dx
\]

By inserting the CDF obtained in (16) into (42), the ergodic rate of the \( N^{th} \) vehicle can be obtained as:

\[
R_{N,M,\infty} = \frac{\alpha N(t) \zeta_v}{\ln 2} \int_0^\infty \left( 1 - \left( \frac{1}{\prod_{i=1}^L \lambda_i} + (-1)^L \sum_{w_0=1}^{L} A_{w_0} e^{-\lambda_{w_0} x} \right)^N \right) dx,
\]

Further, by applying multinomial theorem [58], we can obtain the expression of the rate of the \( N^{th} \) vehicle as [40]. The proof is complete.

\[
R_{N,SC,\infty} = \frac{\alpha N(t) \zeta_v}{\ln 2} \int_0^\infty \frac{\sum_{b_1+b_2+\ldots+b_{mL+1}=L} \left( b_1, b_2, \ldots, b_{mL+1} \right) \prod_{w_0=1}^{mL+1} \left( \lambda_{w_0} x^q e^{-\lambda_{w_0} x} \right)^{b_{w_0}}}{1 + \alpha N(t) x \zeta_v} dx
\]
$U_3$ is affected by the residues of $U_1$ and $U_2$ both. Hence, it is observed that the performance degradation of $U_3$ is higher than $U_2$ due to an increase in the SIC residue. $4 \times 4$ MIMO outperforms $2 \times 2$ MIMO for both the vehicles due to the higher diversity gain of $4 \times 4$ MIMO.

Simulations of rate and sum rate are carried out for SISO-NOMA, SIMO-NOMA and MIMO-NOMA for two vehicles. The power coefficients allocated to $U_1$ and $U_2$ are $\alpha_1 = 0.7$ and $\alpha_2 = 0.3$. The decaying factor for i.n.i.d channel is $\delta = 0.5$. It is assumed that the perfect CSI is available at the receiver. The sum rate performance is also observed with
MMSE channel estimation. For the channel estimation, Pilot signals are transmitted periodically from the BS.

Fig. 9 demonstrates the sum rate vs. SNR performance of two vehicles with SISO, 1×2 SIMO MRC and SC over i.n.i.d Nakagami-m fading channels for m = 1 and m = 2. We can note that the sum rate of SIMO-NOMA is higher than SISO-NOMA. The sum rate is higher in MRC as compared to SC. The sum rate is marginally greater in case of m = 2 as compared to m = 1 for SISO-NOMA. For 1×2 SC, sum rate is lower for m = 2 than m = 1, while for 1×2 MRC, the sum rate remains same for m = 1 and m = 2.

Fig. 10 illustrates the rate performance of U₁ and U₂ with 1×2 MRC for fading parameter m = 2 with high SNR approximation. NOMA outperforms conventional OMA with i.i.d as well as i.n.i.d channel consideration. It can be observed that the rate of U₁ is almost constant as per analysis carried out in (38), while the rate of U₂ increases with the SNR.

The rate performance of U₁ and U₂ of SC-NOMA for m = 2 are presented in Fig. 11. Results show that the rate of U₂ degrades with i.n.i.d channel consideration. Rate of U₂ with SC is marginally lower than MRC and hence, the sum rate with SC is lower than that of MRC. However, the performance improvement in the sum rate of NOMA over conventional OMA is maintained as MRC.

Fig. 12 simulates sum rate performance of 1×2 SIMO and 2×2 MIMO with perfect channel knowledge and MMSE estimation over i.n.i.d channels. It is observed that the sum rate increases as the number of Tx and Rx antennas
The distance between the BS and SIMO-NOMA are simulated for various values of velocities. It is less because of its high diversity gain. Reduction in the sum rate due to channel estimation is almost the same for SISO and MIMO, while the reduction is less in the case of 2 × 2 MIMO because the transmission rate of MIMO increases with an increase in velocity remains same.

Fig. 14 simulates the impact of velocity on the sum rate performance over i.n.i.d channels with channel estimation and SIC residual at t = 3. The performance of MIMO-NOMA based V2I communications have been derived and analyzed over i.n.i.d Nakagami-m fading channels in presence of SIC error propagation. We have considered SISO-NOMA, SIMO-NOMA with MRC and SC and MIMO-NOMA for fading parameter m = 1 and m = 2. NOMA outperforms OMA with i.i.d as well as i.n.i.d consideration. Ergodic sum rate of NOMA is higher than OMA in SIMO and MIMO with perfect channel knowledge and MMSE estimation. With i.n.i.d channel consideration, the outage performance of all the vehicles are degraded and the sum rate is also deteriorated for SIMO-NOMA and MIMO-NOMA as well as OMA. Consideration of i.n.i.d channels cause higher performance degradation with m = 2 as compared to m = 1. Performance deterioration in vehicle with the best channel condition is higher, while less for the vehicles with the worst channel condition. With i.n.i.d assumption, expected diversity gain is not achieved as much as i.i.d assumption and the sum rate is also degraded but the i.n.i.d consideration is more realistic for vehicular communications.

V. CONCLUSION

In this article, outage performance, rate and ergodic sum rate of NOMA based V2I communications have been derived and analyzed over i.n.i.d Nakagami-m fading channels in presence of SIC error propagation. We have considered SISO-NOMA, SIMO-NOMA with MRC and SC and MIMO-NOMA for fading parameter m = 1 and m = 2. NOMA outperforms OMA with i.i.d as well as i.n.i.d consideration. Ergodic sum rate of NOMA is higher than OMA in SIMO and MIMO with perfect channel knowledge and MMSE estimation. With i.n.i.d channel consideration, the outage performance of all the vehicles are degraded and the sum rate is also deteriorated for SIMO-NOMA and MIMO-NOMA as well as OMA. Consideration of i.n.i.d channels cause higher performance degradation with m = 2 as compared to m = 1. Performance deterioration in vehicle with the best channel condition is higher, while less for the vehicles with the worst channel condition. With i.n.i.d assumption, expected diversity gain is not achieved as much as i.i.d assumption and the sum rate is also degraded but the i.n.i.d consideration is more realistic for vehicular communications.

APPENDIX I

PROOF OF LEMMA 1

By substituting (16) in to (17), the CDF of an unordered channel gain of NOMA can be written as:

\[
F_{M,n,||h_n||^2}(x) = \frac{N!}{(N-n)!}(n-1)! \times \sum_{j=0}^{N-n} \frac{(-1)^j}{n+j} \binom{N-n}{j} \times P_1 \quad (47)
\]

where \( P_1 = \left( \frac{\prod_{w=1}^{L} \lambda w}{\prod_{w=1}^{L} \lambda w} + T_1 + T_2 \right)^{n+j} \)
and \( T_1 = (-1)^L \sum_{w=1}^{L} A_w e^{-\lambda w x} \) and \( T_2 = (m - 1) \sum_{w=0}^{L} B_w e^{-\lambda w x} \).
For \( m \in [1, 2] \), \( P_1 \) can be simplified using multinomial theorem as:

\[
P_1 = \sum_{b_1+b_2+\ldots+b_{mL+1}=1}^{n+j} \binom{n+j}{b_1, b_2, \ldots, b_{mL+1}} \left( \frac{n+j}{b_1+b_2+\ldots+b_{mL+1}} \right)
\]

\[
\times \left( \prod_{w=0}^{L} \lambda_w^{m} \right) ^{n+j-b_{mL+1}} \times \left( \prod_{w_0}^{L} A_{w_0} e^{-b_{w_0} \lambda_{w_0} x} \right) \times \left( \prod_{w_0}^{L} ((m-1) B_{w_0} x)^{b_{mL+w_0} e^{-b_{w_0} \lambda_{w_0} x}} \right),
\]

where \( \binom{n+j}{b_1, b_2, \ldots, b_{mL+1}} \) are multinomial coefficients. After substituting \( P_1 \) into (47), the CDF of an ordered channel gain of MRC-NOMA is obtained as (18).

### APPENDIX II

#### B. Calculation of Rate of \( N^{th} \) Vehicle of NOMA with MRC

By inserting \( m = 2 \) and \( L = 1 \) in (43) and considering \( N = 2 \) vehicles, the rate of the \( N^{th} \) vehicle can be written as:

\[
R_{N,M,\infty} = \frac{\alpha_N \zeta_v}{\ln 2} \int_0^\infty \frac{1}{1 + \alpha_N (t) x \zeta_v} \left( 1 - \lambda_1 e^{-\lambda_1 x} - \lambda_2 e^{-\lambda_2 x} \right)^2 dx
\]

\[
R_{N,M,\infty} \text{ can be simplified as:}
\]

\[
R_{N,M,\infty} = \frac{\alpha_N \zeta_v}{\ln 2} \int_0^\infty \frac{1}{1 + \alpha_N (t) x \zeta_v} \left( e^{-2 \lambda_1 x} - \lambda_1^2 x^2 e^{-2 \lambda_1 x} \right) + 2e^{-\lambda_1 x} + 2\lambda_1 x e^{-\lambda_1 x} - 2\lambda_1 x e^{-2 \lambda_1 x} dx
\]

\[
\text{By taking the following approximation at } \zeta_v \to \infty \text{ [48, Eq.37]}
\]

\[
u = \int_0^\infty \frac{x^q e^{-\lambda_1 x}}{1 + \alpha_N (t) x \zeta_v} dx = \frac{\ln(\alpha_N (t) \zeta_v)}{\alpha_N (t) \zeta_v} \Gamma(q) - \frac{\alpha_N (t) \zeta_v^q}{\Gamma(q)} \left( \frac{\alpha_N (t) \zeta_v^q}{\Gamma(q)} \right) q = 0
\]

\[
q > 0
\]

The rate can be written as:

\[
R_{N,M,\infty} \approx \frac{1}{\ln 2} \left( 1 - \frac{\alpha_N (t) \zeta_v}{2\lambda_1} \right)^2 - \lambda_1^2 \Gamma(2) \left( \frac{1}{2\lambda_1} \right)^2 + 2 \ln \left( \frac{\alpha_N (t) \zeta_v}{\lambda_1} \right) + 2 \Gamma(1) \left( \frac{1}{\lambda_1} \right) + 2\lambda_1 \Gamma(1) \left( \frac{1}{2\lambda_1} \right)
\]

Similarly, the rate of the \( N^{th} \) vehicle of NOMA can be simplified with \( 1 \times L \) MRC technique using the multinomial theorem as shown in (40) and then approximated using (50) as (41) in Lemma 2. Using the same method, the rate of the \( N^{th} \) vehicle with \( 1 \times L \) SC is obtained and hence, the sum rate of \( N \) vehicles of SC-NOMA over i.n.i.d Nakagami-\( m \) fading channels.

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