Abstract—Cooperative communications boasts attractive performance enhancements in vehicular communication environment. Amplify and Forward (AF) and Decode and Forward (DF) relaying have been proposed and analysed for vehicular networks in recent literature. For the study of performance enhancements in this area vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) channel model is crucial. Vehicular channel is a mobile to mobile channel which significantly differs from the well known Rayleigh or Nakagami-m channel models. To cater the dynamic nature cascaded fading channel models are introduced. Double Rayleigh fading and double Nakagami fading have been used to analyse AF and DF relaying previously. These models mostly govern Non Line of Sight (N-LOS) communication between transmitting pairs. However, we argue that in cooperative vehicular communication scenarios the likelihood of Line of Sight (LOS) relays are significant and can be subjected to further performance improvement. Supported by several previous works based on practical measurements we model the V2V channel by a double Rician fading process. In DF cooperative VANETs it is highly probable that Source (S)→ Destination (D), S→Relay (R) and R→D pairs have different LOS or N-LOS conditions. With these assumptions and arguments, we investigate the outage performance of DF relaying using analytical formulas and Monte-Carlo simulations. Our results indicate that for V2V DF cooperative relaying, outage probability varies in $1 - 10^{-1}$ region for N-LOS conditions (in both S→R and R→D links) while LOS conditions improves it towards $1 - 10^{-4}$ region when typical V2V Rician K factors are considered. We believe our theoretical analysis could be effectively used to design and improve channel aware routing paradigms for vehicular networks.

I. INTRODUCTION

Cooperative communications fits well in Vehicular networking domain. Requirement for robust and reliable communication protocols in VANETs makes cooperative relaying an ideal counterpart for the lower layers of the protocol stack. Authors of [1] analysed the feasibility of cooperative communications in VANETs. They proposed AF relaying in V2V and V2I communications and performed a diversity analysis. Their results show that AF relaying in vehicular scenarios were able to extract full spatial diversity. Literature on cooperative communications for wireless networks are vast. However, the capabilities of cooperative communications in vehicular domain is yet to be fully explored.

Communication channel in vehicular communications is quite different from the conventional Base Station (BS)→Mobile Station (MS) channel which can be represented by a Rayleigh fading process under N-LOS conditions. The analysis presented in [2] and references therein, have clearly discussed the suitability of cascaded fading models in V2V communication systems. The assumptions are further verified using statistical and measured data for first order and second order scattering in Mobile to Mobile communications. Double cascaded Rayleigh and Nakagami fading channels are used in majority of the work which analyse the cooperative communications in VANETs [1], [3]. These fading models are suitable for N-LOS conditions where the dominant LOS component is obstructed. However, if we consider sparsely populated highway or urban VANET communication environments LOS paths are highly likely to exist.

We assume LOS in S→R and R→D communication pairs for DF relaying in our analysis to fully explore the benefits of cooperative communications in VANETs. For the analysis, we represent the V2V channel with a double cascaded Rician fading process. Selection of this model to represent the V2V channel can be justified by considering the dynamic nature of scatterers and geometry between two vehicles. Even though LOS conditions between two vehicles do not exist all the time this model can reduce to a N-LOS double Rayleigh fading model with a Rician factor equal to zero.

The rest of the paper is organised as follows. Section II presents the related work. In Section III the system model is explained. The simulation setup and the results are described in Section IV. Section V concludes the paper.

II. RELATED WORK

Most of the previous work use either double Rayleigh or Nakagami fading channel to model the V2V channel in vehicular networks. These channel models assume that there are no LOS paths between the transmitter and the receiver. Authors of [3] investigate relay selection in a dual-hop DF cooperative vehicular network. They assume $m$ relaying nodes between S and D. The fading channels $S→R_m$ and $R_m→D$ are assumed to be double Rayleigh fading channels ($R_m$ is the $m^{th}$ relay). Closed form expressions for outage probability and achievable diversity order is derived. However, this analysis is applicable to the N-LOS type of communications in VANETs. In our work this topic is further investigated by considering LOS components in $S→R$ and $R→D$ pairs.

Cooperative diversity for inter-vehicular communications were first discussed in [1]. Double Nakagami-m fading chan-
nels are assumed in this analysis. The authors derive the pair wise error probability performance and diversity order assuming fixed and mobile relay nodes (i.e. fixed roadside infrastructure and vehicles as relays).

We believe that assuming mixed double Rayleigh and Double Rician fading in $S \rightarrow R$ and $R \rightarrow D$ will reveal more insight on the benefits of DF cooperative relaying specially in sparsely populated VANETs. Sparsely populated VANETs are seen as a major challenge in VANETs due to low connectivity.

Double Rician fading channels recently have captured attention of the researchers due to their applicability in the wireless networks. Authors of [4] explore the performance of M-PSK modulation in double Rician fading channels with maximum ratio combining diversity. They have derived the moment generating function of instantaneous SNR in a double Rician fading channel and used it to study the outage performance. However the closed form expressions for the PDF of instantaneous SNR are difficult to be reused in analysing cooperative protocols due to infinite summations and Bessel functions. Their analysis is limited to direct communication model which does not consider cooperative diversity.

In [5], the authors have carried out a V2V RF propagation measurement. The study was based on a LOS setup and important observations were made in terms of Rician factor. They have represented the V2V channel with a Rician fading model and obtained values in the range of 5.0-11.0 for the Rician K factor. The measurement campaign was not generalized to a theoretical model which would have been more useful. Furthermore, the measured results were not compared double Rician fading process.

Some of recent experiment based studies on V2V channel propagations under LOS and N-LOS conditions such as [6], [7], [8] provide interesting motivations to analyse cooperative relaying further in VANETs. Majority of above work do not attempt to explore the outage performance in cooperative VANETs with LOS conditions. Thus we intend to fill this gap by providing a theoretical analysis on vehicular DF cooperative relaying with LOS conditions in $S \rightarrow R$ and $R \rightarrow D$ pairs. We further verify our results with Monte-Carlo simulations.

### III. System Model

When it comes to cooperative communications in vehicular networks, relay positioning is significantly affected by high dynamic nature of the network. The $S \rightarrow D$, $S \rightarrow R$ and $R \rightarrow D$ pairs always will not be positioned ideally as discussed in conventional cooperative communication protocols [1],[3]. Figure 1 illustrates some of these relay position possibilities in single lane and multi lane roads. The work in [9] describes the impact of this scenario with real world measurements in a vehicular network and showed that cooperative relaying outperform conventional schemes with respect to packet error rate. However they failed to demonstrate the properties of the channel and its effect on the performance.

This paper analyses the outage performance of the relay to destination link under LOS conditions. If a link has LOS between communicating nodes (vehicles) $i$ and $j$, the channel
\begin{equation}
\Pr(C \leq \mu_R) = 1 - 4 \frac{(2^{2\mu_R} - 1)}{SNR} \prod_{k=1}^{k} \frac{1}{\lambda_k K_1 \left( \sqrt{4\lambda_1 \lambda_2 \frac{2^{2\mu_R} - 1}{SNR}} \right) \lambda_1 \lambda_2 \left( \sqrt{4\lambda_3 \lambda_4 \frac{2^{2\mu_R} - 1}{SNR}} \right) \lambda_3 \lambda_4} (1)
\end{equation}

\alpha_k \sim (K_k + 1) \lambda_k e^{-K_k} e^{-(K_k + 1) \alpha_k} f_0 \left( 2\sqrt{K_k} (K_k + 1) \alpha_k \lambda_k \right)

\begin{equation}
F_{\alpha_R} (x) = 1 - \int_{0}^{\infty} Q_1 \left( \sqrt{K_1} \frac{2x (K_1 + 1)}{\lambda_2 \alpha_2 SNR} \right) (K_2 + 1) \lambda_2 e^{-K_2} e^{-\lambda_2 \alpha_2 (K_2 + 1)} f_0 \left( 2\sqrt{K_2} (K_2 + 1) \lambda_2 \alpha_2 \right) d\alpha_2 (3)
\end{equation}

\begin{equation}
\Psi_{RD} (x) = \int_{0}^{\infty} Q_1 \left( \sqrt{K_3} \frac{2x (K_3 + 1)}{\lambda_3 \alpha_3 SNR} \right) (K_4 + 1) \lambda_4 e^{-K_4} e^{-\lambda_4 \alpha_4 (K_4 + 1)} f_0 \left( 2\sqrt{K_4} (K_4 + 1) \lambda_4 \alpha_4 \right) d\alpha_4 (4)
\end{equation}

Coefficient \( h_{ij} \) is modeled as \( h_{ij} = h_{i1} h_{j2} \), where \( h_{i1} \) and \( h_{j2} \) are Rice distributed random variables with Ricean factors \( K_1 \) and \( K_2 \). For N-LOS communication pairs \( h_{ij} \) is modeled as the product of two independent complex Gaussian random variables of zero mean and \( \sigma_{h_i}^2, \sigma_{h_j}^2 \) variances [3]. The underlying channels are assumed to be quasi-static. It is further assumed that Additive White Gaussian Noise (AWGN) terms have zero mean and \( N_0 \) variance.

Similar to [1],[3] we assume a half duplex constraint for data transmission which is performed during two time slots. Each transmitter in the network is assumed to be transmitting with a power \( P \) Watts/symbol. We assume perfect decoding of the source information at relay node. However in the case of imperfect decoding of some information relay selection strategy may be employed to enforce similar conditions.

IV. OUTAGE PROBABILITY

A. N-LOS condition in S→R and R→D links

The outage probability for N-LOS conditions in S→R and R→D is analysed in [3]. In their results the outage probability of capacity (\( C_{SR} \)) subjected to a target spectral efficiency \( \mu_R \) is given in (1) where, \( \lambda_i = 1/E(\alpha_i), i = 1,4 \) and \( \alpha_i = |h_{ki}|^2 \), \( k = 1,4 \). At the same time \( SNR = P/N_0 \) where, \( N_0 \) is the noise variance and \( K_1 (\cdot) \) is first order modified Bessel function of the second kind.

B. LOS condition in S→R and R→D links

In Figure 1 we illustrated some possible situations with LOS links for cooperative relaying in vehicular communications along single and multi lane roads. In this section we will analyse the outage of a scenario where both S→R and R→D have LOS links. Assuming a target end-to-end spectral efficiency of \( \mu_R \) per bandwidth the instantaneous capacity of the link \( C_{SR} \) in S→R is expressed in (5). In (5) \( \alpha_{sr} = (P/N_0) \alpha_1 \alpha_2 \) and \( \alpha_k = h_{ki}^2 + h_{kj}^2 \), \( k = 1,4 \). The cascaded Ricean channel coefficients \( h_{ki}, h_{kj} \) are Gaussian random variables with zero mean and non zero variance.

\( C_{sr} = \frac{1}{2} \log_2 (1 + \alpha_{sr}) \leq \mu_R \) (5)

Using the marginal density approach together with (5) we find the CDF of \( \alpha_k, F_{\alpha_{sr}} \) following [3].

\[
F_{\alpha_{sr}} (x) = \Pr (\alpha_{sr} \leq x) = \Pr \left( \alpha_1 \alpha_2 \leq x \frac{SNR}{SNR \alpha_2} \right) f_{\alpha_2} (\alpha_2) d\alpha_2 \]

Th PDF expressed in (2) is used to expand (6) further. Note that the PDF of Ricean distributed random variables contain a Bessel function of first kind which makes it less tractable in calculations. CDF of the same variable contains a Marcum-q function of first order.

\[
\psi_{rd} (x) = 1 - \Psi_{rd} (x)
\]

\[
\Psi_{rd} (x) \text{ is expressed in (4)}.
\]

With similar steps as above, the outage in R→D can be written as,

\[
\Pr (C_{rd} \leq \mu_R) = F_{\alpha_{rd}} (2^{2\mu_R} - 1)
\]

Since we assume LOS link in R→D link using similar steps we can represent the CDF of \( \alpha_{rd} = (P/N_0) \alpha_3 \alpha_4 \) as below.

\[
F_{\alpha_{rd}} (x) = 1 - \Psi_{rd} (x)
\]
Figure 2. Outage Probability comparisons of DF cooperative relaying in LOS and N-LOS conditions, $\mu_n = 1$Hz/bw and $\lambda_i = 1, i = 1, ..4$.

Following [10] a random variable $\gamma_r$ is taken which represents the instantaneous SNR of the DF relay path. The CDF of $\gamma_r$ is written as below [10],

$$Pr(C_{\text{SNR}} \leq \mu_R) = F_{\text{CDF}}(2^{2\mu_R} - 1) \quad (10)$$

Further manipulating (11) we get (12),

$$F_{\gamma_r}(x) = 1 - \Psi_{\text{SNR}}(x) \Psi_{\text{RO}}(x) \quad (11)$$

Using (12) the final outage probability in the relay path, $S \rightarrow R \rightarrow D$ can be written as below,

$$Pr(C_{\gamma} \leq \mu_R) = 1 - \Psi_{\text{SNR}}(2^{2\mu_R} - 1) \Psi_{\text{RO}}(2^{2\mu_R} - 1) \quad (13)$$

where $C_{\gamma}$ is the overall channel capacity over relay path.

C. LOS condition in $S \rightarrow R$ and N-LOS in $R \rightarrow D$ link

As emphasized in Figure 1 in selecting better performing relays there can be instances where the $S \rightarrow R$ is LOS while $R \rightarrow D$ is N-LOS. For such a situation $\alpha_k, k = 1, 2$ will be Rician distributed random variables while $\alpha_k, k = 3, 4$ will be Rayleigh distributed random variables. It should be noted that for $k = 3, 4 \alpha_k \sim \lambda_k e^{-\lambda_k \alpha_k}$. The CDF $F_{\alpha_{\text{SNR}}}$ will be the same with (3) as $S \rightarrow R$ is assumed to be LOS. However $F_{\alpha_{\text{RO}}}(x)$ which describes the outage in the $R \rightarrow D$ link is written in (14) [3].

$$F_{\alpha_{\text{RO}}}(x) = 1 - \sqrt{\frac{4\lambda_3 \lambda_4 x}{\text{SNR}}} K_1 \left( \sqrt{\frac{4\lambda_3 \lambda_4 x}{\text{SNR}}} \right) \quad (14)$$

Following similar steps in subsection B the outage probability in $S \rightarrow R \rightarrow D$ is expressed in (15).

$$V. \text{SIMULATIONS AND RESULTS}$$

We have carried out a set of simulations to verify the analytical expressions in Section IV. The instantaneous capacity of $S \rightarrow R \rightarrow D$ path is calculated assuming DF cooperation at R. An outage event is recorded when the instantaneous capacity is below a target spectral efficiency $\mu_n$. All the nodes are transmitting with power P. For each SNR the capacity calculation is repeated 10000 times. Simulation setup is repeated for the relay position scenarios analysed under in Section IV. We also simulated the outage performance for different Rician-K factors and target spectral efficiencies $\mu_n$.

Outage performance of DF cooperative relays are presented in Figure 2. Cooperative vehicular network with N-LOS links has the worst performance. A significant improvement in the outage performance is observed in networks with LOS links. A drop in outage performance is observed when either $S \rightarrow R$ or $R \rightarrow D$ link is N-LOS. It is also observed that a larger Rician K factor improves outage performance considerably. Thus networks with all LOS links and largest Rician K factor has the best outage performance.

Figure 3 investigates the outage performance for different target spectral efficiencies, $\mu_n = 0.5, 2$Hz/bw for different LOS and N-LOS conditions. For lower data rates outage probabilities are lower for all configurations of $S \rightarrow R \rightarrow D$ path. At all SNR levels the improvement in outage probability is more significant when both $S \rightarrow R$, $R \rightarrow D$ links are of LOS compared to the scenarios where both links are of N-LOS or either link is N-LOS.
\[
Pr (C_r \leq \mu_n) = 1 - \Psi_{SNR} (\frac{2^{2\mu_R} - 1}{\text{SNR}}) \sqrt{\frac{4\lambda_3\lambda_4 (2^{2\mu_R} - 1)}{\text{SNR}}} K_1 \left( \sqrt{\frac{4\lambda_3\lambda_4 (2^{2\mu_R} - 1)}{\text{SNR}}} \right)
\] (15)

VI. Conclusion

In this paper we have analysed a different perspective of DF cooperation in a vehicular network. We highlighted that in a vehicular communication environment, there can be many LOS communication instances which can be exploited to achieve higher performance in terms of outage. We assumed a double Rician fading channel to represent LOS communication between nodes while N-LOS links were modeled by double Rayleigh fading channel. It was observed that a significant improvement in performance is achieved when both the links have LOS components. A drop in outage performance is observed when either S→R or R→D link was N-LOS. When designing network protocols using decode and forward cooperative relaying for vehicular networks, choosing relays with LOS links at all possible instances will lead to higher performance.

REFERENCES