Opportunistic Cooperation for Infrastructure-to-Relaying-Vehicles over LTE-A Networks

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***Abstract*—We extend vehicular cooperation into downlink LTE-A networks in what we call *Infrastructure-to-Relaying-Vehicles* (I2RV) cooperation. In I2RV, vehicles are used as relaying terminals between eNodeB/BS and a receiving user equipment located or mounted on another traveling vehicle, for the aim of extending coverage, improving performance, and attaining distributed transmission. Initial works on cooperative vehicular communications build upon the assumption of flat and quasi-static fading channels, this can be justified only for narrowband systems in very slow traffic flows such as in rush-hours. In this paper, we consider highway traffic with high-speed mobility resulting in doubly-selective (i.e., *time*- and *frequency-selective*) channels. To overcome the performance degradation, we make use of precoded cooperative transmission accompanied with an opportunistic best-relay selection technique to extract the rich underlying multipath-Doppler-spatial diversity gains. Our performance analysis through pairwise error probability (PEP) derivation shows that, through proper precoding, the proposed system is able to extract maximum available diversity in time, frequency and space. Furthermore, we derive a closed-form expressions for the outage probability as a bench-mark for future analysis for the proposed scheme. Through numerical analysis, we demonstrate that significant coverage advantage by extending the transmission distance targeting a specific error rate and using the same transmitting power can be achieved.**

I. Introduction

Long Term Evolution-Advanced (LTE-A), which was ratified by the International Telecommunication Union (ITU) as an IMT-Advanced 4G technology in November 2010, has adopted fixed relaying for cost-effective throughput enhancement and coverage extension [1]. A new approach to create relaying networks has been noted by making use of vehicles equipped with low elevation antennas, short and medium range wireless communication technologies, to extend coverage, enable ad-hoc connectivity and enhance link reliability through distributed spatial diversity. One of the main advantages of vehicular relaying networks are the frequent availability of traveling vehicles, operating in an ad hoc fashion, that eliminates the need for establishing a dedicated relaying infrastructure. Hence, it is envisioned to be a key technology area for significant growth in the coming years, i.e. [2] and the references therein. We remark that the main challenge facing the deployment of the vehicular relaying networks into the LTE-A is the lack of infrastructure, which indeed is happened to be their main advantage. Another challenges comes from extending the relaying network area and the high-speed moving vehicles. In most practical scenarios, inter-symbol interference (ISI) due to the multipath fading nature of the channel introduces frequency-selectivity while Doppler spreads result in time-selectivity. To realize the full potential of cooperative diversity using vehicular relaying, it is a requirement to have an in-depth investigation of performance limits, as well as development of enabling techniques to support such broadband transmission.

In this paper we investigate the performance and outage gains of a transmission scheme in downlink LTE-A networks where vehicles act as relaying cooperating terminals for eNodeB-to-User equipment (UE) downlink session, the destination UE is considered located or mounted in a traveling vehicle through a highway traffic. The associated wireless links are characterized by a doubly-selective fading channel which results in performance degradation in terms of error probability. Hence, we use a precoded cooperative transmission technique to extract the underlying rich multipath-Doppler-spatial diversity. Furthermore, we implement a best-relay selection scheme to take advantage of the potentially large number of available relaying vehicles.

We further contribute by 1) The derivation of a closed-form error rate expression as a bench mark to assess our analysis and future research studies of such an approach. 2) Our analytical and simulation results shows a significant diversity gains which are achievable through the precoding transmission and the relay selection technique. 3) The study of our proposed model, indicates that the error rates can be tremendously reduced. 4) A noticeable reduction in the required transmitting powers compared to the traditional transmission schemes is observed. 5) Providing a derived outage probability closed form expression as a benchmark for future assessments.

The paper is organized as follows. In Section II, we describe the proposed dual-hop cooperative system, using an opportunistic best relay-selection over R available vehicles willing to be involved in the transmission session. In Section III, we derive the pairwise error probability (PEP) expression and demonstrate the achievable diversity gains, in addition to the derivation of the outage probability. In Section IV, we present numerical results to confirm the analytical derivations and

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provide insight into the system performance. Finally, Section V concludes paper.

Notations: $(.)^{\mathrm{T}}$, $(.)^{*}$ and $(.)^{\mathrm{H}}$ denotes transpose, conjugate and Hermitian operations, respectively. $\mathbb{E}[.]$, $|.|$ and $\otimes$ denotes expectation, absolute value and Kronecker product, respectively. $[\mathbf{H}]_{k,m}$ represents the (k,m)-th entry of $\mathbf{H}$. $\mathbf{I}_N$ indicates an $N \times N$-size identity matrix. $\mathbf{1}$ and $\mathbf{0}$ represents, respectively, all-ones and all-zeros matrix with proper dimensions. $\lceil . \rceil$ and $\lfloor . \rfloor$ denotes integer ceil and integer floor operations, respectively. $*$ is the convolution operator. x, i, j, k are dummy variables. $F(.)$ and $f(.)$ is the cumulative distribution function (CDF) and probability density function (pdf), respectively. Bold letters denote the matrices and vectors.

II. System Model

We consider an infrastructure-to-relaying vehicle (I2RV) assisted communication scheme. Source (S) models the eNodeB/BS, relay (R) models the relaying vehicle and destination (D) models the receiving vehicle "UE", each are equipped with single transmit and receive antennas, and operate in half-duplex mode. To reflect the relay geometry, we consider an aggregate channel model which takes into account both path-loss and small-scale fading. Path loss is proportional to d^{α} where α is the path loss coefficient and d is the propagation distance. The path loss associated with the distance d from the eNodeB to the UE is modeled as

$$\Omega(d) = 10^{(128.1 - 36.7\log_{10} d)/10} \tag{1}$$

Let d_{sd}, d_{sr} and d_{rd} denote the distances of source-to-destination (S→D), source-to-relay (S→R), and relay-to-destination (R→D) links, respectively, and θ is the angle between lines S→R and R→D. Normalizing the path loss in S→D to be unity, the relative geometrical gains are defined respectively as $G_{sr} = (d_{sd}/d_{sr})^{\alpha}$ and $G_{rd} = (d_{sd}/d_{rd})^{\alpha}$.

As for short-term fading, terminals are located within a highly scattering highway/sub-urban area, while the relay and destination have low elevation antennas. Accordingly the channel is characterized as single Rayleigh-double Doppler. We adopt the double-ring channel model which assumes that the scattering reflectors lay uniformly over a ring around the mobile terminal [3]. The channel autocorrelation function is

$$R(\tau) = \sigma^2 J_0\left(\frac{2\pi}{\lambda} v_1 \tau\right) J_0\left(\frac{2\pi}{\lambda} v_2 \tau\right) \tag{2}$$

where $J_0(.)$ is the zero order Bessel function, λ is the wavelength of the carrier frequency, σ^2 is the channel variance and v_1 and v_2 are the communicating terminals' maximum relative velocity. Define f_D as the maximum Doppler shift results from the relative motion of the two communicating terminals, given by $f_D = 2\pi((v_1 + v_2)/\lambda)$. Note that in vehicular channel there are several instantaneous velocities due to acceleration/decelerations. The earlier defined maximum Doppler shift f_D has been therefore calculated based on the maximum velocities experienced. We can further define the Doppler spread given by $f_d = 1/T_d$, where T_d is the coherence time of the channel. Due to the fast vehicles mobility, the channel is subject to time-frequency selectivity quantified through delay spread τ_d. If the channel satisfies the condition $2 f_d \tau_d < 1$, it can be classified as doubly-selective [4]. We make use of the *Receive Diversity* (RD) protocol of [5] with *Decode-and-Forward* (DF) relaying. In the broadcasting phase, the source transmits its signal to the relaying vehicle and the destination. In the relaying phase, the relaying vehicle decodes its received precoded signal based on maximum likelihood (ML) detector. In practice, the relay can decide that an incorrect decision has been made through cyclic redundancy check (CRC) deployment, then forwards a fresh copy of the precoded signal to destination. The destination again makes its decision based on ML detector. The block diagram of the system is shown in Fig. 1.

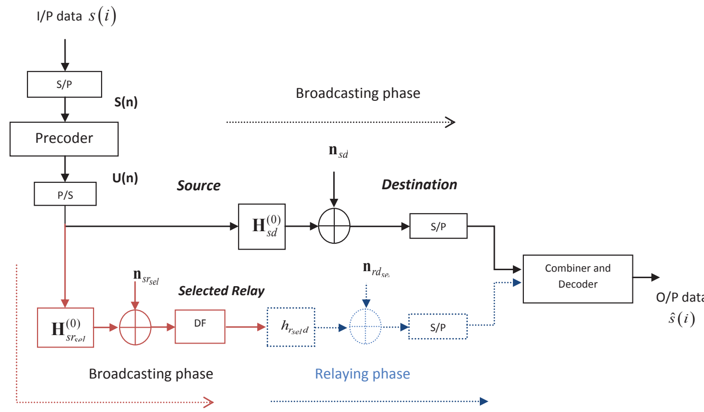

Fig. 1: Precoded I2RV cooperative transmission scheme.

The precoder used is designed to ensure the maximum diversity over doubly-selective channels and to eliminate the inter-block interference (IBI) term. It is given by $\boldsymbol{\Theta} = \mathbf{F}_{P+Q}^{\mathrm{H}} \mathbf{T_1} \otimes \mathbf{T_2}$, where $\mathbf{F}_{P+Q}^{\mathrm{H}}$ is $(P+Q)$-point IFFT matrix, $\mathbf{T}_1 := [\mathbf{I}_P,\ \mathbf{0}_{P\times Q}]^{\mathrm{T}}$ and $\mathbf{T}_2 := [\mathbf{I}_Z,\ \mathbf{0}_{Z\times L}]^{\mathrm{T}}$. Here, $P \geq 1$ and $Z \geq 1$ are the precoder design parameters such that $N_s = PZ$, $N_t = (P+Q)(Z+L)$. We have $L = \lceil \tau_d/T_s \rceil$ as the number of the resolvable multipath components and the number of Doppler shifts experienced over the data block is given by $Q = \lceil N_t T_s f_d \rceil$ [4]. A DFT is used to render a discrete finite sequence of complex coefficients, given by

$$\mathbf{s}(n) = \sum_{q=0}^{Q} s(n)\, e^{-jw_q} \tag{3}$$

here $w_q = 2\pi(q - Q/2)/N_t$ is the finite Fourier bases that capture the time variation. Based on the so-called Basis Expansion Model (BEM), a discrete-time baseband equivalent channel for the doubly-selective channel can be expressed as

$$h_B(a;l) = \sum_{q=0}^{Q} h_q(n;l) e^{j2w_q a} \qquad , l \in [0, L] \tag{4}$$

where $h_q(n;l)$ is zero-mean complex Gaussian. Here, a denotes the serial index for the input data symbols and the block index is given by $n = \lfloor a/N_t \rfloor$. For the cooperative scheme under consideration, define $\mathbf{H}_{sd,q}^{(0)}$, $\mathbf{H}_{sr,q}^{(0)}$ and $\mathbf{H}_{rd,q}^{(0)}$ as the lower triangular Toeplitz channel matrices with entries given by (4). Let L_{sd}, L_{sr} and L_{rd} denote the channel multipath lengths for the S→D, S→R and R→D links, respectively. Further, let Q_{sd}, Q_{sr} and Q_{rd} denote the number of resolvable Doppler components for corresponding links.

In the broadcasting phase, the received signals at the relay can be expressed in a matrix form as

$$\mathbf{y}_{sr}\left(n\right) = \sqrt{G_{sr}E_s}\sum_{q=0}^{Q}\mathbf{D}(w_q)\mathbf{H}_{sr,q}^{(0)}\left(n\right)\mathbf{u}\left(n\right) + \mathbf{n}_{sr}\left(n\right) \quad (5)$$

where $\mathbf{u}(n) = \mathbf{\Theta}\mathbf{s}(n)$ is the transmitted data block, $Q = \max\left(Q_{sd}, Q_{sr}, Q_{rd}\right)$ and E_s is the modulated symbol energy. We have $\mathbf{D}(w_q) := \mathrm{diag}[1, \ldots, \exp(jw_q(N_t-1))]$ and $\mathbf{n}_{sr}(n)$ the S→R additive white Gaussian noise (AWGN) vector with entries of zero mean and $N_0/2$ variance. Using the commutativity of products of Toeplitz matrices with vectors, we can replace $\mathbf{H}_{sr,q}^{(0)}(n)\mathbf{u}(n)$ with $\mathbf{U}(n)\mathbf{h}_{sr,q}(n)$, and rewrite (5) as

$$\mathbf{y}_{sr}\left(n\right) = \sqrt{G_{sr}E_s}\sum_{q=0}^{Q}\mathbf{D}(w_q)\mathbf{U}\left(n\right)\mathbf{h}_{sr,q}\left(n\right) + \mathbf{n}_{sr}\left(n\right) \quad (6)$$

Defining the augmented matrix $\mathbf{h}_{sr}\left(n\right) = [\mathbf{h}_{sr,0}^{\mathrm{T}}\left(n\right)\cdots\mathbf{h}_{sr,Q}^{\mathrm{T}}\left(n\right)]^{\mathrm{T}}$ and $\mathbf{\Phi}\left(n\right) = \left[\begin{array}{ccc}\mathbf{D}(w_0)\mathbf{U}(n) & \cdots & \mathbf{D}(w_Q)\mathbf{U}(n)\end{array}\right]$, we have

$$\mathbf{y}_{sr}\left(n\right) = \sqrt{G_{sr}E_s}\mathbf{\Phi}\left(n\right)\mathbf{h}_{sr}\left(n\right) + \mathbf{n}_{sr}\left(n\right) \quad (7)$$

similarly, the received signal at the destination during the broadcasting phase

$$\mathbf{y}_{sd}\left(n\right) = \sqrt{E_s}\mathbf{\Phi}\left(n\right)\mathbf{h}_{sd}\left(n\right) + \mathbf{n}_{sd}\left(n\right) \quad (8)$$

where $\mathbf{n}_{sd}(n)$ is the associated S→D AWGN vector with entries of zero mean and $N_0/2$ variance. During the relaying phase, the relay received signals are fed to the ML. The relay forwards a fresh copy of the precoded signal; we have the received signal during the relaying phase at destination

$$\mathbf{y}_{rd}\left(n\right) = \sqrt{G_{rd}E_s}\mathbf{\Phi}\left(n\right)\mathbf{h}_{rd}\left(n\right) + \mathbf{n}_{rd}\left(n\right) \quad (9)$$

with $\mathbf{n}_{rd}(n)$ as the associated R→D AWGN vector with entries of zero mean and $N_0/2$ variance. Finally, arranging (8) and (9) in matrix form, we have

$$\underbrace{\left[\begin{array}{c}\mathbf{y}_{sd}\left(n\right)\\ \mathbf{y}_{rd}\left(n\right)\end{array}\right]}_{\mathbf{Y}(n)} = \underbrace{\sqrt{E_s}\left[\begin{array}{cc}\mathbf{\Phi}\left(n\right) & 0\\ 0 & \sqrt{G_{rd}}\mathbf{\Phi}\left(n\right)\end{array}\right]}_{\mathbf{S}(n)}\underbrace{\left[\begin{array}{c}\mathbf{h}_{sd}\left(n\right)\\ \mathbf{h}_{rd}\left(n\right)\end{array}\right]}_{\mathbf{h}(n)} + \underbrace{\left[\begin{array}{c}\mathbf{n}_{sd}\left(n\right)\\ \mathbf{n}_{rd}\left(n\right)\end{array}\right]}_{\mathbf{n}(n)} \quad (10)$$

ML detection is then performed at the destination. The above signal model developed for single relay can be easily extended for a multi-relay scenario with relay selection. Let $\dot{\gamma}_{sd}\left(n\right)$, $\dot{\gamma}_{sr_i}\left(n\right)$ and $\dot{\gamma}_{r_id}\left(n\right)$ denotes the average SNRs for the associated links. The best relay will be chosen based on

$$r_{sel} = \arg\max_{r_i}\left\{\min\left(\dot{\gamma}_{sr_i}, \dot{\gamma}_{r_id}\right)\right\} \quad (11)$$

III. Pair-wise Error Probability and Diversity Gain Derivation

We consider the case of an opportunistic relay-selection for the I2RV cooperative scheme over *R* available relaying vehicles willing to be involved in the transmission. The cooperation is selected from multiple relays to provide extra reliability and enhanced distributed transmission. With d_{sr_i} and d_{r_id} denotes the distances for the associated relaying vehicle, and θ_i is the angle between lines $\mathrm{S} \rightarrow \mathrm{R}_i$ and $\mathrm{R}_i \rightarrow \mathrm{D}$, here $i = 1, 2, \ldots, R$. The relative geometrical gains are defined as $G_{sr_i} = \left(d_{sd}/d_{sr_i}\right)^{\alpha}$ and $G_{r_id} = \left(d_{sd}/d_{r_id}\right)^{\alpha}$, which can be further defined using the law of cosines as $G_{sr_i}^{-2/\alpha} + G_{r_id}^{-2/\alpha} - 2G_{sr_i}^{-2/\alpha}G_{r_id}^{-2/\alpha}\cos\theta_i = 1$. In the following, we will investigate relay selection based on the best cooperative link associated SNR, (i.e. Opportunistic Relaying (OR)). The performance metric will follow the PEP expression in [6]

$$\begin{aligned} P_{R_{sel}}&\left(\mathbf{S}\rightarrow\hat{\mathbf{S}}\middle|\mathbf{h}_{sd}, \mathbf{h}_{sr_i}, \mathbf{h}_{r_id}\right)\\ &\leq P_{Coop_i}\left(\mathbf{S}\rightarrow\hat{\mathbf{S}}\middle|\mathbf{h}_{sd}, \mathbf{h}_{r_id}\right)\\ &\quad + P_{sr_i}\left(\mathbf{S}\rightarrow\hat{\mathbf{S}}\middle|\mathbf{h}_{sr_i}\right)P_{sd}\left(\mathbf{S}\rightarrow\hat{\mathbf{S}}\middle|\mathbf{h}_{sd}\right) \end{aligned} \quad (12)$$

where $P_{Coop_i}\left(n\right)$ is the PEP for the relay selection cooperative transmission, $P_{sr_i}\left(n\right)$ is the PEP for the $\mathrm{S}\rightarrow\mathrm{R}_i$ and $P_{sd}\left(n\right)$ is the error probability of $\mathrm{S}\rightarrow\mathrm{D}$ link. Using the lower bounds recently proposed in [7], entries in (12) can be tightly lower bounded by

$$P\left(\mathbf{S}\rightarrow\hat{\mathbf{S}}\middle|\mathbf{h}\right) \approx \sum_{m=1}^{3}\varepsilon_m\exp\left(-\frac{\rho_m}{4N_0}d^2\left(\mathbf{S},\hat{\mathbf{S}}\middle|\mathbf{h}\right)\right) \quad (13)$$

where $\varepsilon_1 = \varepsilon_2 = 2\varepsilon_3 = 1/12$, $\rho_1 = 12\left(\sqrt{3}-1\right)/\pi$, $\rho_2 = 4\left(3-\sqrt{3}\right)/\pi$ and $\rho_3 = 2\sqrt{3}/\pi$. The Euclidean distance conditioned on the fading channel coefficients is $d^2\left(\mathbf{S}\rightarrow\hat{\mathbf{S}}\middle|\mathbf{h}\right) = \mathbf{h}^{\mathrm{H}}\left(\mathbf{S}-\hat{\mathbf{S}}\right)^{\mathrm{H}}\left(\mathbf{S}-\hat{\mathbf{S}}\right)\mathbf{h}$. (12) can be rewritten as

$$\begin{aligned} P_{R_{sel}}\left(\mathbf{S}\rightarrow\hat{\mathbf{S}}\middle|\mathbf{h}_{sd}, \mathbf{h}_{sr_i}, \mathbf{h}_{r_id}\right) &\leq \sum_{m=1}^{3}\varepsilon_m e^{\left(-\frac{\mathbf{h}_{sd}^H\chi\mathbf{h}_{sd}}{4}\frac{E_s}{N_o}\right)}\\ \times&\left(e^{\left(-\rho_m\frac{G_{sr_i}\mathbf{h}_{sr_i}^H\chi\mathbf{h}_{sr_i}}{4}\frac{E_s}{N_o}\right)} + e^{\left(-\rho_m\frac{G_{r_id}\mathbf{h}_{r_id}^H\chi\mathbf{h}_{r_id}}{4}\frac{E_s}{N_o}\right)}\right) \end{aligned} \quad (14)$$

where $\mathbf{h}_{sr_i}$ and $\mathbf{h}_{r_id}$ are the associated channel vector for the $\mathrm{S}\rightarrow\mathrm{R}_i$ and $\mathrm{R}_i\rightarrow\mathrm{D}$ links respectively. By using eigen value decomposition and following the analysis in [2], we define the associated channel gain for each link as $\gamma_{sd} = \mathbf{h}_{sd}^{\mathrm{H}}\chi\mathbf{h}_{sd} = \sum_{p=0}^{\mathrm{r}_{sd}-1}\lambda_p|\beta_p^{sd}|^2$, $\gamma_{sr_i} = G_{sr_i}\mathbf{h}_{sr_i}^{\mathrm{H}}\chi\mathbf{h}_{sr_i} = G_{sr_i}\sum_{k=0}^{\mathrm{r}_{sr_i}-1}\alpha_k|\beta_k^{sr_i}|^2$ and $\gamma_{r_id} = G_{r_id}\mathbf{h}_{r_id}^{\mathrm{H}}\chi\mathbf{h}_{r_id} = G_{r_id}\sum_{j=0}^{\mathrm{r}_{r_id}-1}\kappa_j|\beta_j^{r_id}|^2$. Where r_{sd}, r_{sr_i} and r_{r_id} are the ranks of the auto-correlation matrices for the associated channels. With λ_p, α_k and κ_j as the eigen values of the associated matrices. Define $\gamma_i = \min_i\left(\gamma_{sr_i}, \gamma_{r_id}\right)$ and its complement $\gamma_i^{'} = \max_i\left(\gamma_{sr_i}, \gamma_{r_id}\right)$. Considering that $-\infty \leq \left(\gamma_i - \gamma_i^{'}\right) \leq 0$ and assuming that the selected relay is very close to the destination, hence $G_{sr_i} \ll G_{r_i d}$ and $\gamma_i \ll \gamma_i^{'}$. We can take upper bound to (14). From (11), we get

$$P_{R_{sel}}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\dot{\gamma}_{sd},\dot{\gamma}_b\right)\le e^{-\left(\frac{\dot{\gamma}_{sd}+\dot{\gamma}_b}{4}\right)} \tag{15}$$

where $\dot{\gamma}=\dot{\gamma}_{sd}+\dot{\gamma}_b$ is the total end-to-end SNR for the I2RV scheme under relay-selection based on SNR, $\dot{\gamma}_{sd}=\gamma\gamma_{sd}$ is the end-to-end SNR for S $\rightarrow$ D link and $\dot{\gamma}_b=\arg\max_{r_i}(\dot{\gamma}_i)$, i.e. $\dot{\gamma}_i=\gamma^{d_i}\gamma_i$ is the end-to-end SNR for the relaying link S $\rightarrow$ R_i $\rightarrow$ D, and $d_i=\min(\mathrm{r}_{sr_i},\mathrm{r}_{r_i d})$. In the following analysis, we need to get the probability distribution function (pdf) of $\dot{\gamma}$. The CDF of $\dot{\gamma}_i$ will have the form [8]

$$F_{\dot{\gamma}_i}(x)=1-P_{sr_i}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\gamma_{sr_i}>x\right)P_{r_i d}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\gamma_{r_i d}>x\right) \tag{16}$$

Since $\dot{\gamma}_{sr_i}$ and $\dot{\gamma}_{r_i d}$ are summations of weighted independent exponential distributed random variables, they follow a 'Hypoexponential distribution' also known as the generalized 'Erlang distribution' [9]. The pdf of γ_i is given by $f_{\dot{\gamma}_i}(x)=dF_{\dot{\gamma}_i}(x)/dx$

$$f_{\gamma_i}(x)=\sum_{j_1=0}^{\mathrm{r}_{sr_i}-1}\sum_{j_2=0}^{\mathrm{r}_{r_i d}-1}\left(c_{i,j_1,j_2}\left(\alpha_{i,j_1}+\kappa_{i,j_2}\right)e^{-\left(\alpha_{i,j_1}+\kappa_{i,j_2}\right)x}\right) \tag{17}$$

where

$$c_{i,j_1,j_2}=\left(\prod_{\substack{\neq j_1\\=0}}^{\mathrm{r}_{sr_i}-1}\frac{\alpha_{i,k}}{(\alpha_{i,k}-\alpha_{i,j_1})}\right)\left(\prod_{\substack{\neq j_2\\=0}}^{\mathrm{r}_{r_i d}-1}\frac{\kappa_{i,k}}{(\kappa_{i,k}-\kappa_{i,j_2})}\right) \tag{18}$$

from $\dot{\gamma}_b=\max_i(\dot{\gamma}_i)$, we have

$$F_{\dot{\gamma}_b}(x)=P\left(\max_{i\in R}(\dot{\gamma}_i)<x\right)=\prod_{i=1}^{R}P(\dot{\gamma}_i<x) \tag{19}$$

using the property $\sum\sum c_{i,j_1,j_2}=1$ [9], from (19)

$$F_{\dot{\gamma}_b}(x)=\prod_{i=1}^{R}\left(\tfrac{1}{\bar{\gamma}_i}-\tfrac{1}{\bar{\gamma}_i}\sum_{j_1=0}^{\mathrm{r}_{sr_i}-1}\sum_{j_2=0}^{\mathrm{r}_{r_i d}-1}\left(c_{i,j_1,j_2}e^{-\left(\alpha_{i,j_1}+\kappa_{i,j_2}\right)x}\right)\right) \tag{20}$$

For the general case modeled by independent non-identical distributed (i.n.i.d.) channels, using the following property [10]

$$\prod_{k=1}^{R}(1+x_k)=1+\sum_{k=1}^{R}\sum_{j_1=1}^{R-k+1}\sum_{j_2=j_1+1}^{R-k+2}\cdots\sum_{j_k=j_{k-1}+1}^{R}\prod_{n=1}^{k}x_{j_n} \tag{21}$$

and after some mathematical derivations, the pdf for the end-to-end SNR $\dot{\gamma}$ is expressed as (22) at the top of the next page.

The unconditional PEP for the I2RV multi-relay selection and DF, can be evaluated by averaging the expression in (15) and using the pdf shown in (22), we have (23) shown at the top of the next page. Where

$$A_{i,j_1,j_2}=\left(\frac{4\rho_m\gamma}{4+\rho_m\gamma}-\frac{4}{1+4\left(\alpha_{p_i,j_1}+\kappa_{p_i,j_2}\right)}\right),$$

and

$$C_{p_i,j_1,j_2}=\frac{\rho_m\gamma\left(\alpha_{p_i,j_1}+\kappa_{p_i,j_2}\right)c_{i,j_1,j_2}}{\rho_m\gamma\left(\alpha_{p_i,j_1}+\kappa_{p_i,j_2}\right)-1}$$

For i.n.i.d relay-selection I2RV (23) and sufficiently high SNR, the asymptotical diversity gain $D_{gain,R}$ is the exponent associated with the resulting SNR, and is given by

$$D_{gain,R}=\mathrm{r}_{sd}+R \tag{24}$$

From (24), we observe that the maximum asymptotical diversity gain is bounded by the rank of the auto-correlation matrix associated with the S $\rightarrow$ D channel, added to the number of relaying vehicles willing to be involved in the transmission. If the relative traveling velocity of the relaying vehicle with respect to the designated vehicle is not equal to zero, extra diversity gains can be extracted from the S $\rightarrow$ R_i $\rightarrow$ D link.

The outage probability P_{out} is the probability that error probability exceeds a specified value $\dot{\gamma}_{th}$. Mathematically speaking $P_{out}=\int_0^{\dot{\gamma}_{th}}f_{\dot{\gamma}}(\dot{\gamma})\,d\dot{\gamma}$ [11], which is the cumulative distribution function (CDF) of $\dot{\gamma}$, namely $F_{\dot{\gamma}}(\dot{\gamma}_{th})$. By defining our un-normalized aggregate channel model which takes into account both path-loss and small-scale fading, the relative geometrical gain are re-defined as $G_{sd}=d_{sd}^{-\alpha}$, $G_{sr}=d_{sr}^{-\alpha}$ and $G_{rd}=d_{rd}^{-\alpha}$. These can be related to one another through the cosine theorem $G_{sr}^{-2/\alpha}+G_{rd}^{-2/\alpha}-2G_{sr}^{-1/\alpha}G_{rd}^{-1/\alpha}\cos\theta=G_{sd}^{-2/\alpha}$, and assuming a normalized gain for a 1m distance [12]. Hence $\gamma_{sd}=G_{sd}\mathbf{h}_{sd}^{\mathrm{H}}\chi\mathbf{h}_{sd}=G_{sd}\sum_{p=0}^{\mathrm{r}_{sd}-1}\lambda_p|\beta_p^{sd}|^2$. From (22) and the definition of CDF, the outage probability is given by

$$P_{out,co}=\sum_{m=1}^{3}\varepsilon_m\sum_{k=1}^{R}\sum_{p_1=1}^{R-k+1}\sum_{p_2=p_1+1}^{R-k+2}\cdots\sum_{p_k=p_{k-1}+1}^{R}\frac{(-1)^{k+1}}{\rho_m\gamma}\prod_{i=1}^{k}\Psi_i \tag{25}$$

where

$$\Psi_i=\sum_{j_1=0}^{\mathrm{r}_{sr_{p_i}}-1}\sum_{j_2=0}^{\mathrm{r}_{r_{p_i}d}-1}C_{p_i,j_1,j_2}\times\left(\rho_m\gamma\left(1-e^{\left(-\frac{1}{\rho_m\gamma}\right)\dot{\gamma}_{th}}\right)-\frac{1-e^{-\left(\alpha_{p_i,j_1}+\kappa_{p_i,j_2}\right)\dot{\gamma}_{th}}}{\alpha_{p_i,j_1}+\kappa_{p_i,j_2}}\right)$$

In (25), the d_{sd} can be shown as an effective parameter on the resulting outage probability of our proposed scheme .

IV. Numerical and Simulation Results

In this section, we demonstrate the performance gains of the proposed scheme using numerical results from our mathematical model, as well as simulation results using the MATLAB simulator. As defined in the standard, LTE-A targets peak data rates up to 1 Gb/s with up to 100 MHz supported spectrum bandwidth and QPSK modulation is used [1]. Unless otherwise stated, we consider $f_c=2.5$GHz, $\mathrm{T_s}=500\mu s$, $v_r=v_d=120$km/h, $\alpha=3.67$, $\theta=\pi$, $G_{sr}/G_{rd}=-30$dB and $\tau_d=1.328$ μs [13]. We assume perfect channel state information is available at the receiving terminals. We use the precoder Θ with parameters $P=2$ and $Z=2$. This results in $[L_{sd},Q_{sd}]=[1,1]$ for the S $\rightarrow$ D and S $\rightarrow$ R links. Due to the zero relative velocity for the R $\rightarrow$ D link, a frequency-time flat channel is used, hence $[L_{coop},Q_{coop}]=[0,0]$.

$$f_{\dot{\gamma}}\left(x\right)=\sum_{k=1}^{R}\sum_{p_1=1}^{R-k+1}\cdots\sum_{p_k=p_{k-1}+1}^{R}\frac{(-1)^{k+1}}{\gamma}\prod_{i=1}^{k}\left(\frac{1}{\bar{\gamma}_i}\sum_{j_1=0}^{\mathrm{r}_{sr p_i}-1}\sum_{j_2=0}^{\mathrm{r}_{r p_i d}-1}\frac{\gamma\left(\alpha_{p_i,j_1}+\kappa_{p_i,j_2}\right)c_{i,j_1,j_2}}{\gamma\left(\alpha_{p_i,j_1}+\kappa_{p_i,j_2}\right)-1}\left(e^{\left(-\frac{1}{\gamma}\right)x}-e^{-\left(\alpha_{p_i,j_1}+\kappa_{p_i,j_2}\right)x}\right)\right) \tag{22}$$

$$P_{R_{sel}}\left(\mathbf{s}\to\hat{\mathbf{s}}\right)\approx\sum_{m=1}^{3}\varepsilon_m\sum_{k=1}^{R}\sum_{p_1=1}^{R-k+1}\sum_{p_2=p_1+1}^{R-k+2}\cdots\sum_{p_k=p_{k-1}+1}^{R}\frac{(-1)^{k+1}}{\rho_m\gamma}\prod_{i=1}^{k}\left(\frac{1}{\bar{\gamma}_i}\sum_{j_1=0}^{\mathrm{r}_{sr p_i}-1}\sum_{j_2=0}^{\mathrm{r}_{r p_i d}-1}A_{i,j_1,j_2}C_{i,j_1,j_2}\right) \tag{23}$$

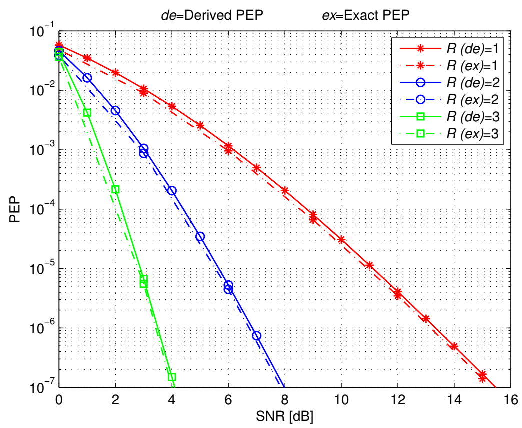

Fig. 2: Comparison of derived PEP in (23) and exact PEP.

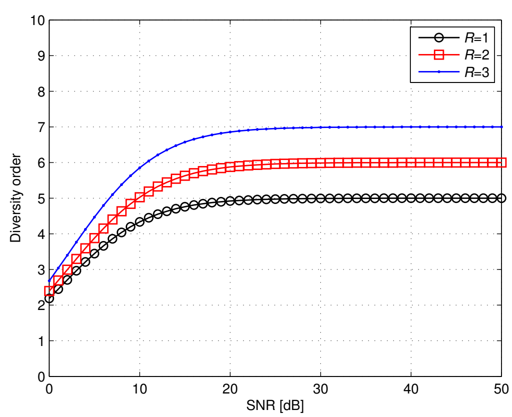

Fig. 3: Diversity orders for the relay-selection I2RV scenario.

In Fig. 2 we verify our analytical derivations by comparing the derived PEP expressions (23) with the exact PEP expressions. Exact PEP can be found by taking the expectation numerically for $P(\mathbf{S}\to\hat{\mathbf{S}}\big|\,\mathbf{h})=Q\left(\sqrt{(1/2N_0)\,d^2\left(\mathbf{S},\hat{\mathbf{S}}\big|\,\mathbf{h}\right)}\right)$ [3], through random generation of the underlying $\mathbf{h}_{sd}$, $\mathbf{h}_{sr_i}$ and $\mathbf{h}_{r_id}$ links, and using proper statistics via numerical techniques. We consider $R=1$, 2 and 3 available relaying vehicles and the relay involved in cooperation is selected based on the criteria given by (11). We observe that the derived PEP provides a good tight upper bound on the exact one, with $\simeq$ 0.5dB difference, the slope changes in the performance curve illustrates the diversity advantage gain. In Fig. 3 we plot the slope of our proposed scheme to precisely observe the gain we succeeded to achieve, the achieved diversity orders is consistent with (24) and equal to $D_{gain,R}=5$, 6 and 7, compared to $D_{gain,R}=1$ for traditional direct transmission.

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V. Conclusion

In this paper, we present an I2RV scheme, in which eNodeB/BS point communicates to a designated vehicle traveling through a highway. Cooperating relaying vehicles is used to deliver data over LTE-Advanced down-link session. To achieve higher performance gains, an opportunistic best-relay selection model is proposed. Further we provide analytical analysis to model and evaluate the proposed scheme. We investigate its performance under the practical assumption of the doubly-selective fading channels. To extract the underlying rich diversity, we employ precoded cooperative transmission. Through the derivation of PEP and outage probability, we demonstrate that full diversity gains are achieved.

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