On the Performance Analysis of Cooperative Vehicular Relaying in LTE-A Networks

Mohamed F. Feteiha and Hossam S. Hassanein

Telecommunications Research Lab (TRL)
School of Computing
Queen's University
Kingston, Ontario, Canada, K7L 3N6
Email:{feteiha, hossam}@cs.queensu.ca

***Abstract*—We investigate the performance gains of a transmission scheme in LTE-A networks where vehicles act as relaying cooperating terminals. The advantages of vehicular relaying networks are the abundant energy and computing power, the predictable mobility patterns of vehicles, and the availability of information from positioning systems and map-based technologies. The frequent availability of traveling vehicles, operating in an ad hoc fashion, eliminates the need for establishing a dedicated relaying infrastructure. However, the associated wireless links are characterized by a doubly-selective fading channel. This causes performance degradation in terms of error probability. Hence, we propose a precoded cooperative transmission technique to extract the underlying rich multipath-Doppler-spatial diversity. Furthermore, we implement a relay selection scheme to take advantage of the potentially large number of available relaying vehicles. We further contribute by 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. Our analytical and simulation results indicate that significant diversity gains are achievable, and that error rates can be greatly reduced. As well, there is a noticeable reduction in the required transmitting powers compared to the traditional transmission schemes.**

I. Introduction

The evolution of Fourth Generation (4G) mobile communication is envisaged to permit new services and usage models with higher efficiency protocols to be used in roaming and communicating within the network anytime, anywhere using a multiplicity of wireless technologies. 4G systems are expected to support wide range of applications that require higher data rates and reliable transmission. To meet such demand, wireless communication system designers need to advance and optimize the network performance in terms of better link reliability, fewer dropped connections and longer battery life. Long Term Evolution-Advanced (LTE-A), which was ratified by the International Telecommunication Union (ITU) as an IMT-Advanced 4G technology in November 2010, constitutes a significant milestone in the evolution of 4G systems, and is expected to dominate the next generation of wireless networks. LTE-A, has adopted relaying for cost-effective throughput enhancement and coverage extension [1], [2].

The utilization of multihop relaying techniques is aimed at increasing network performance without the need to undergo high costs in expanding a networks infrastructure. The main principle in relaying results in reduced levels of power consumption for the mobile terminals. This is the outcome of reducing the transmitter to receiver distance and hence the required transmission power. In addition they provide higher throughput, increase coverage, lower operational and capital expenditure allow for faster roll out, and a more flexible configuration. 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 [3]–[6].

Characteristically advantages of vehicular relaying networks are: 1) the abundant energy and computing power. 2) Unlike general mobile ad hoc networks, vehicles can have very predictable movement. 3) Roadway information is often available from positioning and map-based technologies. 4) Given the average speed and road trajectory, the future position of a vehicle can be predicted. In addition to the previous advantages, the frequent availability of traveling vehicles, operating in an ad hoc fashion, eliminates the need for establishing a dedicated relaying infrastructure. Hence, vehicular relaying is envisioned to be a key technology area for significant growth in the coming years. Although the expectations for this emerging technology are set very high, many practical aspects remain unsolved. The main challenge facing the deployment of the vehicular relaying networks indeed comes from their main advantage, i.e., the lack of infrastructure. Vehicular relays suffer from frequent changes in connectivity and association. As well, the associated wireless links are characterized by a doubly-selective fading channel. This causes performance degradation in terms of error probability. To realize the full potential of cooperative diversity using vehicular relaying for LTE-A networks, it is important to conduct an in-depth investigation of performance limits and gains, as well as development of enabling techniques to support such broadband transmission [1], [6]. To best of the authors knowledge, such a study does not exist in the literature.

In this paper we investigate the performance gains of a transmission scheme in LTE-A networks where vehicles act as relaying cooperating terminals for eNodeB-to-User equipment (UE) downlink session. To overcome, the doubly-selective fading channel, we propose a precoded cooperative transmission

978-1-4673-2480-9/13/$31.00 ©2013 IEEE

technique to extract the underlying rich multipath-Doppler-spatial diversity. we further propose 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 show significant diversity gains. 3) Our results also indicate that the error rates can be tremendously reduced. 4) As well, a noticeable reduction in the required transmitting powers.

The remainder of the paper is organized as follows: In Section II, we describe the proposed dual-hop cooperative system, using a best relay-selection from *M* available vehicles willing to be involved in the transmission session. In Section III, we derive the Pair-wise Error probability (PEP) expression and demonstrate the achievable diversity gains. In Section IV, we present numerical results to confirm the analytical derivations and provide insight into the system performance. Finally, we conclude in Section V.

Notation: $(.)^{\mathrm{T}}$, $(.)^{*}$ and $(.)^{\mathrm{H}}$ denotes transpose, conjugate and Hermitian operations, respectively. $\mathbb{E}[.]$, $|.|$ and $\otimes$ denotes expectation, absolute value and Kronecker product, respectively. Bold letters denote matrices and vectors. $[\mathbf{H}]_{k,m}$ 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 floor operations, respectively. $*$ is convolution operator. x, i, j, k are dummy variables. $F(.)$ and $f(.)$ is the cumulative distribution function (CDF) and probability density function (pdf) for a given random variable, respectively.

II. System Model

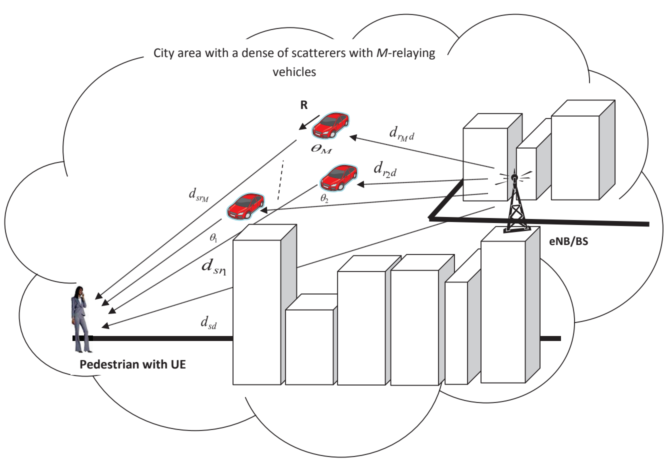

Fig. 1: Cooperative relaying vehicles transmission over LTE-A, using *M*-relays deployment.

We consider a cooperative communication scenario as shown in Figure 1, where an eNodeB antenna (source) communicates directly with UE (destination), and indirectly through a relaying vehicle (R) that serves as a best selected relaying terminal. All terminals are assumed to be equipped with single transmit and receive antennas, and operate in half-duplex mode. We assume an orthogonal cooperation protocol of [7] with decode-and-forward (DF) relaying. In the broadcasting phase, the source transmits its precoded signal to the relaying vehicle and the destination. In the relaying phase, the relay is engaged in forwarding the received signal only if it was decoded correctly, otherwise the relay is silent. The relay decodes and then forwards a fresh decoded copy of the precoded signal to the destination. The destination makes its decision based on the two received signals over the broadcasting and relaying phases. Our aggregate channel model takes into account both small-scale fading and path-loss. 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 $\Omega(d) = 10^{(128.1+36.7\log_{10}d)/10}$.

Let d_{sd} denote the distance from source S to destination D ($\mathrm{S} \rightarrow \mathrm{D}$), with d_{sr_i} and $d_{r_i d}$ respectively denoting the distances ($\mathrm{S} \rightarrow \mathrm{R}_i$) and ($\mathrm{R}_i \rightarrow \mathrm{D}$), $i = 1, 2, \ldots, M$. θ_i is the angle between lines $\mathrm{S} \rightarrow \mathrm{R}_i$ and $\mathrm{R}_i \rightarrow \mathrm{D}$. The relative geometrical gains are defined as $G_{sr_i} = (d_{sd}/d_{sr_i})^{\alpha}$ and $G_{rd_i} = (d_{sd}/d_{r_i d})^{\alpha}$, and can be further defined using the law of cosines as $G_{sr_i}^{-2/\alpha} + G_{rd_i}^{-2/\alpha} - 2G_{sr_i}^{-2/\alpha} G_{r_i d}^{-2/\alpha} \cos\theta_i = 1$.

As for short-term fading, it should be noted that relaying vehicles and destination UE have low elevation antennas and are located within a highly scattering urban area. This requires considering the local scattering around transmitters and receivers. The time correlation function is given by $C(\Delta t) = \sigma^2 J_0\left(\frac{2\pi}{\lambda} v_2 \Delta t\right) J_0\left(\frac{2\pi}{\lambda} v_1 \Delta t\right)$, where v_1 and v_2 are the velocities of the two communicating terminals, J_0 is the zero order Bessel function, λ is the wavelength of the carrier frequency, σ^2 is the channel variance. We have a stationary eNodeB antenna (i.e, $v_e = 0$). Assuming single Rayleigh distribution with a single Doppler shift, the power spectrum and time correlation mathematical functions reduce to having the autocorrelation function and the power spectrum of the complex envelope. These are respectively given by $C(\tau) = \sigma^2 J_0(2\pi v_r \tau/\lambda)$ and $S(f) = \sigma^2 (\pi f_{D_m} \sqrt{1 - (f/f_{D_m})^2})^{-1}$, with v_r being the maximum velocity of relaying vehicles. We can further define the Doppler spread given by $f_d = 1/T_D$, where T_D is the coherence time of the channel. Besides time-selectivity results from the Doppler shifts, the channel is subject to frequency-selectivity quantified through delay spread τ_d. The channel satisfies the *under-spread doubly-selective* condition $2 f_d \tau_d < 1$ [8]. The time-sampled OFDM signal is converted into the frequency domain by implementing a discrete Fourier transform (DFT). The DFT renders a discrete finite sequence of complex coefficients, which are given by

$$\mathbf{s}(n) = \sum_{q=0}^{Q} s(n) e^{-j w_q} \tag{1}$$

where $w_q = 2\pi (q - Q/2)/N_t$ is the finite Fourier bases that capture the time variation, and N_t is the number of the input data symbols per each data block. From (1), a modified Basis Expansion Model (BEM) can be used to represent a discrete-time baseband equivalent channel for the vehicular doubly-selective channel under consideration, and is given by

$$h_B(\ell; l) = \sum_{q=0}^{Q} h_q(n; l) e^{j2w_q\ell}, l \in [0, L] \quad (2)$$

where $h_q(n; l)$ is zero-mean complex Gaussian. Here, ℓ denotes the serial index for the input data symbols. The block index is given by $n = \lfloor \ell / N_t \rfloor$.

The input data blocks at the transmitter (generated from an M-QAM constellation) of length N_t are divided into shorter sub-blocks of length N_s ($N_s \leq N_t$). Let each of these sub-blocks be denoted by $\mathbf{s}(n)$ which are the input to a linear precoder $\mathbf{\Theta}$ of size $N_s \times N_t$. We have $N_s = PZ$, $N_t = (P+Q)(Z+L)$. The number of the resolvable multipath components is given by $L = \lceil \tau_d / T_s \rceil$ and the number of Doppler shifts experienced over the data block is given by $Q = \lceil N_t T_s f_d \rceil$, we have T_s as the symbols duration. 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 (2). 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

$$\mathbf{y}_{sr}(n) = \sqrt{G_{sr}E_s} \sum_{q=0}^{Q} \mathbf{D}(w_q)\mathbf{H}_{sr,q}^{(0)}(n)\,\mathbf{u}(n) + \mathbf{n}_{sr}(n) \quad (3)$$

where $\mathbf{u}(n) = \mathbf{\Theta}\mathbf{s}(n)$ is the transmitted data block, $Q = \max(Q_{sd}, Q_{sr}, Q_{rd})$ 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 commutativity of products of Toeplitz matrices with vectors, we replace $\mathbf{H}_{sr,q}^{(0)}(n)\mathbf{u}(n)$ with $\mathbf{U}(n)\mathbf{h}_{sr,q}(n)$, and rewrite (3) as

$$\mathbf{y}_{sr}(n) = \sqrt{G_{sr}E_s} \sum_{q=0}^{Q} \mathbf{D}(w_q)\mathbf{U}(n)\,\mathbf{h}_{sr,q}(n) + \mathbf{n}_{sr}(n) \quad (4)$$

Defining the augmented matrices $\mathbf{h}_{sr}(n) = [\ \mathbf{h}_{sr,0}^{\mathrm{T}}(n) \ \cdots \ \mathbf{h}_{sr,Q}^{\mathrm{T}}(n)\ ]^{\mathrm{T}}$ and $\mathbf{\Phi}(n) = [\ \mathbf{D}(w_0)\mathbf{U}(n) \ \cdots \ \mathbf{D}(w_Q)\mathbf{U}(n)]$, we have

$$\mathbf{y}_{sr}(n) = \sqrt{G_{sr}E_s}\mathbf{\Phi}(n)\,\mathbf{h}_{sr}(n) + \mathbf{n}_{sr}(n) \quad (5)$$

Similarly, the received signal at the destination during the broadcasting phase is given by

$$\mathbf{y}_{sd}(n) = \sqrt{E_s}\mathbf{\Phi}(n)\,\mathbf{h}_{sd}(n) + \mathbf{n}_{sd}(n) \quad (6)$$

where $\mathbf{n}_{sd}(n)$ is the associated S→D AWGN vector with entries of zero mean and $N_0/2$ variance. During relaying phase, the relay-received signals are fed to the ML detector

$$\arg\min_{\bar{\mathbf{s}}} \left\{ \left\| \mathbf{y}_{sr}(n) - \sqrt{G_{sr}E_s} \sum_{q=0}^{Q} \mathbf{D}(w_q)\mathbf{H}_{sr,q}^{(0)}(n)\,\mathbf{\Theta}\bar{\mathbf{s}} \right\|^2 \right\} \quad (7)$$

with $\bar{\mathbf{s}}$ as all possible signal block combinations. We implement "ideal DF" at relay [9], the relay then forwards a fresh decoded copy of the received precoded signal, i.e., $\dot{\mathbf{u}}(n)$. The received signal during relaying phase at destination is then

$$\mathbf{y}_{rd}(n) = \sqrt{G_{rd}E_s}\dot{\mathbf{\Phi}}(n)\,\mathbf{h}_{rd}(n) + \mathbf{n}_{rd}(n) \quad (8)$$

where $\mathbf{n}_{rd}(n)$ is the associated R→D AWGN vector with entries of zero mean and $N_0/2$ variance. $\dot{\mathbf{\Phi}}(n) = [\ \mathbf{D}(w_0)\dot{\mathbf{U}}(n) \ \cdots \ \mathbf{D}(w_Q)\dot{\mathbf{U}}(n)\ ]$. Finally, arranging (6) and (8) in matrix form, we have

$$\mathbf{Y}(n) = \mathbf{S}(n)\,\mathbf{h}(n) + \mathbf{n}(n) \quad (9)$$

in (9), we have

$$\mathbf{Y}(n) = [\ \mathbf{y}_{sd}(n) \quad \mathbf{y}_{rd}(n)\ ]^{\mathrm{T}},$$

$$\mathbf{S}(n) = \sqrt{E_s}\mathrm{diag}[\ \mathbf{\Phi}(n) \quad \sqrt{G_{rd}}\dot{\mathbf{\Phi}}(n)\ ],$$

$$\mathbf{h}(n) = [\ \mathbf{h}_{sd}(n) \quad \mathbf{h}_{rd}(n)\ ]^{\mathrm{T}}$$

and

$$\mathbf{n}(n) = [\ \mathbf{n}_{sd}(n) \quad \mathbf{n}_{rd}(n)\ ]^{\mathrm{T}}$$

Maximum Likelihood (ML) detection is then performed at the destination with the metric form

$$\arg\min_{\bar{\mathbf{s}}} \left\{ \left\| \mathbf{y}_{sd}(n) - \sqrt{E_s} \sum_{q=0}^{Q} \mathbf{D}(w_q)\mathbf{H}_{sd,q}^{(0)}(n)\,\mathbf{\Theta}\bar{\mathbf{s}} \right\|^2 + \left\| \mathbf{y}_{rd}(n) - \sqrt{G_{rd}E_s} \sum_{q=0}^{Q} \mathbf{D}(w_q)\mathbf{H}_{rd,q}^{(0)}(n)\,\bar{\dot{\mathbf{u}}} \right\|^2 \right\} \quad (10)$$

with $\bar{\dot{\mathbf{u}}}$ as all the possible block combinations for the relayed signal.The above signal model developed for single relay can be easily extended for a multi-relay scenario with relay selection. Let $\dot{\gamma}_{sd}(n)$, $\dot{\gamma}_{sr_i}(n)$ and $\dot{\gamma}_{r_i d}(n)$ denotes the average end-to-end SNRs per block for the S → D, S → R_i and R_i → D links, respectively.

The best relay is selected as the relay node that can achieve the highest signal-to-noise ratio at the destination node. Since the performance gains of the cooperative link S→R→D is bounded by the minimum of the individual S→R and R→D links [10], the relay selection will follow

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

with r_{sel} as the metric used for selecting the best relaying vehicle. The received signal matrix has similar form as in (9).

III. PEP Derivation and Diversity Gain Analysis

In this section, we investigate the achievable diversity gain order for the precoded cooperative communication, using the best-relaying vehicular. We assume perfect CSI at the relay and destination. For the orthogonal cooperative protocol with DF relaying, after removing the block index n for mathematical convenience, the PEP at the destination node is given by [9]

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

with $\hat{\mathbf{S}}$ representing the erroneously decoded data matrix instead of the originally transmitted $\mathbf{S}$. $P_{R_{sel}}\left(\mathbf{S}\to\hat{\mathbf{S}}\right)$ is the end-to-end PEP, $P_{sr_i}\left(\mathbf{S}\to\hat{\mathbf{S}}\right)$ is the PEP results from the S $\to$ R$_i$ link, $P_{sd}\left(\mathbf{S}\to\hat{\mathbf{S}}\right)$ is the PEP results from the S $\to$ D link and $P_{Coop_i}\left(\mathbf{S}\to\hat{\mathbf{S}}\right)$ is the PEP results from the cooperative link (i.e., S $\to$ R$_i$ and R$_i$ $\to$ D, in the case that the relay detects the signal correctly but the signal resulting from the cooperative link is detected wrong). The conditional PEP for each individual term in (12) is given by [11]

$$P(\mathbf{S}\to\hat{\mathbf{S}}|\,\mathbf{h}) = Q\left(\sqrt{\frac{1}{2N_0}d^2\left(\mathbf{S},\hat{\mathbf{S}}\middle|\,\mathbf{h}\right)}\right) \quad (13)$$

Using the lower bounds recently proposed in [12], (13) can be tightly lower bounded by

$$P\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\mathbf{h}\right) \approx \sum_{m=1}^{3}\varepsilon_m e^{\left(-\frac{\rho_m}{4N_0}d^2\left(\mathbf{S},\hat{\mathbf{S}}|\mathbf{h}\right)\right)} \quad (14)$$

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 $d^2\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\mathbf{h}\right) = \mathbf{h}^{\mathrm{H}}\left(\mathbf{S}-\hat{\mathbf{S}}\right)^{\mathrm{H}}\left(\mathbf{S}-\hat{\mathbf{S}}\right)\mathbf{h}$. Starting with $P_{Coop_i}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\mathbf{h}\right)$, (14) can be rewritten as

$$P_{Coop_i}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\mathbf{h}\right) \approx \sum_{m=1}^{3}\varepsilon_m e^{\left(-\frac{\mathbf{h}_{sd}^{\mathrm{H}}\boldsymbol{\chi}\mathbf{h}_{sd}+G_{r_id}\mathbf{h}_{r_id}^{\mathrm{H}}\boldsymbol{\chi}\mathbf{h}_{r_id}}{4}\rho_m\gamma\right)} \quad (15)$$

where $\boldsymbol{\chi} = \left(\boldsymbol{\Phi}-\hat{\boldsymbol{\Phi}}\right)^{\mathrm{H}}\left(\boldsymbol{\Phi}-\hat{\boldsymbol{\Phi}}\right)$. Note that the channel autocorrelation matrix is given by $\mathbf{C}_{h,sd} := \mathbb{E}[\mathbf{h}_{sd}\mathbf{h}_{sd}^{\mathrm{H}}]$, and the channel rank is $r_a := \mathrm{rank}(\mathbf{C}_{h,sd}) \leqslant (Q_{sd}+1)(L_{sd}+1)$. For the S $\to$ D link, we have $Q_{sd}=0$ and $r_a \leqslant (L_{sd}+1)$. Using the eigenvalues decomposition of the autocorrelation matrix, we have $\mathbf{C}_{h,sd} = \mathbf{V}_{sd}\mathbf{D}_{sd}\mathbf{V}_{sd}^{\mathrm{H}}$ where $\mathbf{D}_{sd} := \mathrm{diag}[\sigma_0^2,\sigma_1^2,\ldots,\sigma_{r_a-1}^2]$ and $\mathbf{V}_{sd}\mathbf{V}_{\underline{sd}}^{\mathrm{H}} = \mathbf{I}_{r_{sd}}$. Let the normalized channel vector be denoted as $\bar{\mathbf{h}}_{sd}$ of size $r_a \times 1$ whose entries are independent and identically distributed (i.i.d.) Gaussian random variables with zero mean and unit variance. We can replace $\mathbf{h}_{sd}$ with $\mathbf{V}_{sd}\mathbf{D}_{sd}^{1/2}\bar{\mathbf{h}}_{sd}$ since both will have identical distribution, so the PEP will remain statistically invariant. Further define $\mathbf{A}_{sd} := \left(\mathbf{V}_{sd}\mathbf{D}_{sd}^{1/2}\right)^{\mathrm{H}}\boldsymbol{\chi}\mathbf{V}_{sd}\mathbf{D}_{sd}^{1/2}$, where $\mathbf{A}_{sd}$ is Hermitian (i.e. $\mathbf{A}_{sd} = \mathbf{A}_{sd}^{\mathrm{H}}$), so there exists a unitary matrix $\bar{\mathbf{V}}_{sd}$ and a real non-negative definite matrix $\bar{\mathbf{D}}_{sd}$ such that $\bar{\mathbf{V}}_{sd}^{\mathrm{H}}\mathbf{A}_{sd}\bar{\mathbf{V}}_{sd} := \bar{\mathbf{D}}_{sd}$. The eigenvector of $\mathbf{A}_{sd}$ is $\bar{\mathbf{D}}_{sd} := \mathrm{diag}[\lambda_0,\lambda_1,\ldots,\lambda_{r_a-1}]$. Since $\bar{\mathbf{V}}_{sd}$ is unitary, the vector $\tilde{\mathbf{h}}_{sd} = \bar{\mathbf{V}}_{sd}\bar{\mathbf{h}}_{sd}$ will have correlation matrix identical to $\bar{\mathbf{h}}_{sd}$, namely we have $\tilde{\mathbf{C}} := \mathbb{E}[\tilde{\mathbf{h}}_{sd}\tilde{\mathbf{h}}_{sd}^{\mathrm{H}}] = \mathbb{E}[\bar{\mathbf{V}}_{sd}\bar{\mathbf{h}}_{sd}\bar{\mathbf{h}}_{sd}^{\mathrm{H}}\bar{\mathbf{V}}_{sd}^{\mathrm{H}}]$. From (15), we have

$$\begin{aligned} P_{Coop_i}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\mathbf{h}\right) \\ \approx \sum_{m=1}^{3}\varepsilon_m e^{\left(-\frac{G_{r_id}\mathbf{h}_{r_id}^{\mathrm{H}}\boldsymbol{\chi}\mathbf{h}_{r_id}}{4}\rho_m\gamma\right)}e^{\left(-\frac{\tilde{\mathbf{h}}_{sd}^{\mathrm{H}}\mathbf{A}_{sd}\tilde{\mathbf{h}}_{sd}}{4}\rho_m\gamma\right)} \end{aligned} \quad (16)$$

We obtain $P_{sd}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\mathbf{h}_{sd}\right)$ and $P_{sr_i}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\mathbf{h}_{sr_i}\right)$ by following similar steps

$$\begin{aligned} P_{R_{sel}}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\mathbf{h}_{sd},\mathbf{h}_{sr_i},\mathbf{h}_{r_id}\right) \\ \leq \sum_{m=1}^{3}\varepsilon_m e^{-\frac{\gamma_{sd}}{4}\rho_m\gamma}\left(e^{-\frac{\gamma_{sr_i}}{4}\rho_m\gamma}+e^{-\frac{\gamma_{r_id}}{4}\rho_m\gamma}\right) \end{aligned} \quad (17)$$

where $\gamma_{sd} = \mathbf{h}_{sd}^{\mathrm{H}}\boldsymbol{\chi}\mathbf{h}_{sd} = \sum_{p=0}^{r_{sd}-1}\lambda_p|\beta_p^{sd}|^2$, $\gamma_{sr_i} = G_{sr_i}\mathbf{h}_{sr_i}^{\mathrm{H}}\boldsymbol{\chi}\mathbf{h}_{sr_i} = G_{sr_i}\sum_{k=0}^{r_{sr_i}-1}\alpha_k|\beta_k^{sr_i}|^2$ and $\gamma_{r_id} = G_{r_id}\mathbf{h}_{r_id}^{\mathrm{H}}\boldsymbol{\chi}\mathbf{h}_{r_id} = G_{r_id}\sum_{j=0}^{r_{r_id}-1}\kappa_j|\beta_j^{r_id}|^2$. Define $\gamma_i = \min_i(\gamma_{sr_i},\gamma_{r_id})$ and $\gamma_i^{'} = \max_i(\gamma_{sr_i},\gamma_{r_id})$. Note that $-\infty \leq \left(\gamma_i-\gamma_i^{'}\right) \leq 0$. Based on [13], the best relaying location is by selecting a relay which is close to the destination, hence $G_{sr_i} \ll G_{r_id}$ and $\gamma_i \ll \gamma_i^{'}$. We can rewrite (17) as

$$P_{R_{sel}}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\dot{\gamma}_{sd},\dot{\gamma}_b\right) \leq \sum_{m=1}^{3}\varepsilon_m e^{-\rho_m\frac{\dot{\gamma}_{sd}+\dot{\gamma}_b}{4}} \quad (18)$$

where $\dot{\gamma}_{sd} = \gamma\gamma_{sd}$ is the SNR results from the S $\to$ D link. $\dot{\gamma}_b = \arg\max_{r_i}(\dot{\gamma}_i)$, i.e. $\dot{\gamma}_i = \gamma^{d_i}\gamma_i$, is the SNR results from the relaying link S $\to$ R$_i$ $\to$ D, where $d_i = \min(r_{sr},r_{rd})$. Define $\dot{\gamma} = \dot{\gamma}_{sd}+\dot{\gamma}_b$ as the total end-to-end SNR. The CDF of $\dot{\gamma}_i$ is given by [14]

$$\begin{aligned} F_{\dot{\gamma}_i}(x) \\ = 1 - P_{sr_i}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\gamma_{sr_i}>x\right)P_{r_id}\left(\mathbf{S}\to\hat{\mathbf{S}}\middle|\,\gamma_{r_id}>x\right) \end{aligned} \quad (19)$$

$\dot{\gamma}_{sr_i}$ and $\dot{\gamma}_{r_id}$ are a summation of weighted independent exponential distributed random variables [15] and follow the hypoexponential distribution also known as the generalized Erlang distribution, and will have the pdfs based on [16]

$$f(\gamma_{sr_i}) = \sum_{j=0}^{r_{sr_i}-1}\left(\alpha_{i,j}e^{-\left(\alpha_{i,j}\gamma_{sr_i}\right)}\prod_{\substack{k\neq j\\k=0}}^{r_{sr_i}-1}\frac{\alpha_{i,k}}{(\alpha_{i,k}-\alpha_{i,j})}\right)$$

and

$$f(\gamma_{r_id}) = \sum_{j=0}^{r_{r_id}-1}\left(\kappa_{i,j}e^{-\left(\kappa_{i,j}\gamma_{r_id}\right)}\prod_{\substack{k\neq j\\k=0}}^{r_{r_id}-1}\frac{\kappa_{i,k}}{(\kappa_{i,k}-\kappa_{i,j})}\right)$$

The pdf of $\dot{\gamma}_i$ can then be calculated and results in the form

$$\begin{aligned} f_{\dot{\gamma}_i}(x) \\ = \sum_{j_1=0}^{r_{sr_i}-1}\sum_{j_2=0}^{r_{r_id}-1}\left(c_{i,j_1,j_2}\left(\alpha_{i,j_1}+\kappa_{i,j_2}\right)e^{-\left(\alpha_{i,j_1}+\kappa_{i,j_2}\right)x}\right) \end{aligned} \quad (20)$$

where

$$c_{i,j_1,j_2} = \left(\prod_{\substack{k\neq j_1\\k=0}}^{r_{sr_i}-1} \frac{\alpha_{i,k}}{(\alpha_{i,k}-\alpha_{i,j_1})}\right)\left(\prod_{\substack{k\neq j_2\\k=0}}^{r_{r_id}-1} \frac{\kappa_{i,k}}{(\kappa_{i,k}-\kappa_{i,j_2})}\right) \tag{21}$$

The average SNR for the relaying link $\mathrm{S} \rightarrow \mathrm{R}_i \rightarrow \mathrm{D}$ is given by $\bar{\gamma}_i = \mathbb{E}[\dot{\gamma}_i]$. Recalling the definition of $\dot{\gamma}_b = \max_i(\dot{\gamma}_i)$, we have

$$F_{\dot{\gamma}_b}(x) = P\left(\max_{i\in R}(\dot{\gamma}_i) < x\right) = \prod_{i=1}^{R} P(\dot{\gamma}_i < x) \tag{22}$$

where

$$\begin{aligned} P(\dot{\gamma}_i < x) &= \int_0^x f_{\dot{\gamma}_i}(z)\,dz \\ &= \tfrac{1}{\bar{\gamma}_i}\sum_{j_1=0}^{r_{sr_i}-1}\sum_{j_2=0}^{r_{r_id}-1}\left(c_{i,j_1,j_2} - c_{i,j_1,j_2}e^{-\left(\alpha_{i,j_1}+\kappa_{i,j_2}\right)x}\right) \end{aligned} \tag{23}$$

noting $\sum\sum c_{i,j_1,j_2} = 1$ [16]. In the following, assuming independent identical distributed (i.i.d.) channels, the unconditional PEP can be evaluated first by averaging (18). From (22) and (23), we obtain

$$F_{\dot{\gamma}_b}(x) = \left(\frac{1}{\bar{\gamma}_i} - \frac{1}{\bar{\gamma}_i}\sum_{j_1=0}^{r_{sr}-1}\sum_{j_2=0}^{r_{rd}-1}\left(c_{j_1,j_2}e^{-\left(\alpha_{j_1}+\kappa_{j_2}\right)x}\right)\right)^M \tag{24}$$

note that the relay index i have been removed for the sake of presentation. The pdf of $\dot{\gamma}_b$ is given by

$$\begin{aligned} &f_{\dot{\gamma}_b}(x) \\ &= \tfrac{M}{(\bar{\gamma}_i)^M}\left(\sum_{j_1=0}^{r_{sr}-1}\sum_{j_2=0}^{r_{rd}-1} c_{j_1,j_2}\left(\alpha_{j_1}+\kappa_{j_2}\right)e^{-\left(\alpha_{j_1}+\kappa_{j_2}\right)x}\right) \\ &\quad\times\left(1-\sum_{j_1=0}^{r_{sr}-1}\sum_{j_2=0}^{r_{rd}-1} c_{j_1,j_2}e^{-\left(\alpha_{j_1}+\kappa_{j_2}\right)x}\right)^{M-1} \end{aligned} \tag{25}$$

Using the binomial theorem [18] along with some mathematical manipulations, we rewrite (25) in compact form as

$$f_{\dot{\gamma}_b}(x) = A\sum_{j_3=0}^{M-1} B_{j_3}\mathcal{K}_{j_3} \tag{26}$$

where

$$A = \frac{M}{(\bar{\gamma}_i)^M}\sum_{j_1=0}^{r_{sr}-1}\sum_{j_2=0}^{r_{rd}-1}\left(\alpha_{j_1}+\kappa_{j_2}\right) \tag{27}$$

$$B_{j_3} = \binom{M-1}{j_3}(-1)^{j_3}\left(\prod_{p_3=0}^{r_{sr}-1}\prod_{p_4=0}^{r_{rd}-1} c_{p_3,p_4}^{j_3}\right) \tag{28}$$

$$\begin{aligned} &\mathcal{K}_{j_3} = \\ &\sum_{p_5=0}^{r_{sr}-1}\sum_{p_6=0}^{r_{rd}-1}\left(c_{p_5,p_6}e^{-\left(\left(\alpha_{p_5}+\kappa_{p_6}\right)+j_3\sum_{p_1=0}^{r_{sr}-1}\sum_{p_2=0}^{r_{rd}-1}\left(\alpha_{p_1}+\kappa_{p_2}\right)\right)x}\right) \end{aligned} \tag{29}$$

Further, the pdf for the $\mathrm{S} \rightarrow \mathrm{D}$ link is given by

$$f(\gamma_{sd}) = \sum_{j=0}^{r_{r_id}-1}\left(\lambda_{i,j}e^{-\left(\lambda_{i,j}\gamma_{r_id}\right)}\prod_{\substack{k\neq j\\k=0}}^{r_{r_id}-1}\frac{\lambda_{i,k}}{(\lambda_{i,k}-\lambda_{i,j})}\right) \tag{30}$$

The pdf for the end-to-end SNR is

$$f_{\dot{\gamma}}(x) = f_{\dot{\gamma}_{sd}}(x) * f_{\dot{\gamma}_b}(x) \tag{31}$$

where $\dot{\gamma} = \dot{\gamma}_{sd} + \dot{\gamma}_b$. Substituting (26) and (30) in (31) , and defining

$$\begin{aligned} &\mathcal{G}_1 = \\ &\left(\frac{4D_{j_3,p_5,p_6,p_7}}{1+4\left(\alpha_{p_5}+\kappa_{p_6}\right)+4j_3\sum_{p_1=0}^{r_{sr}-1}\sum_{p_2=0}^{r_{rd}-1}\left(\alpha_{p_1}+\kappa_{p_2}\right)} - \frac{4\rho_m\gamma D_{j_3,p_5,p_6,p_7}}{4+\rho_m\lambda_{p_7}\gamma}\right) \end{aligned}$$

we have the resulting PEP as

$$P_{\mathrm{i}}\left(\mathbf{S}\rightarrow\hat{\mathbf{S}}\right) \leqslant \sum_{m=1}^{3}\varepsilon_m A\sum_{p_7=0}^{r_{sd}-1}\sum_{j_3=0}^{M-1}\left(B_{j_3}\sum_{p_5=0}^{r_{sr}-1}\sum_{p_6=0}^{r_{rd}-1}\mathcal{G}_1\right) \tag{32}$$

From (32), at sufficiently high SNR, we find that the asymptotic diversity gain $D_{gain,M}$ is given by

$$D_{gain,M} = r_{sd} + M\left(\min\left(r_{sr}, r_{rd}\right)\right) \tag{33}$$

from (33), the divesrity gain is function of the number of relaying vechiles involved in the best-relay selection, as well as the channel order of all the underlying links.

IV. Numerical and Simulation Results

In this section, we present the numerical results to demonstrate the error rate performance advantages achieved from our proposed scheme. LTE-A addresses those challenges by targeting peak data rates up to 1 Gb/s with up to 100 MHz supported spectrum bandwidth and by making use of high-order multiple antennas transmission [2]. Unless otherwise stated, we consider QPSK modulation and assume $f_c = 2.5\text{GHz}$, $\mathrm{T_s} = 500\mu s$, $v_r = 60\text{km/h}$, $\alpha = 3.67$, $\theta = \pi$, $G_{sr}/G_{rd} = -30\text{dB}$ and $\tau_d = 1.328\ \mu\text{s}$ [17]. We assume that perfect channel state information is available at the receiving terminals. We use the precoder $\mathbf{\Theta}$ with parameters $P = 2$ and $Z = 2$. This results in $[L_{Coop}, Q_{Coop}] \in ([0,0],[0,1],[1,0],[1,1])$ for $\mathrm{S}\rightarrow\mathrm{R}$ and $\mathrm{R}\rightarrow\mathrm{D}$ links. A frequency-time flat channel is used for $\mathrm{S}\rightarrow\mathrm{D}$ link, i.e. $[L_{sd}, Q_{sd}] = [0,0]$. Further, in urban areas it is reasonable to expect that a significant portion of the vehicular communication will be bound to the road surface. Thus making the LOS between two communicating nodes with one of them as a vehicle having a low elevated antenna, susceptible to interruptions by other vehicles. It is likely that other vehicles, especially large public transportation and commercial vehicles such as buses and trucks, will often obstruct the LOS and results in a Rayleigh distributed channels.

In Figure 2, we illustrate the PEP expression (32), compared to the exact "analytical" expression (12). Exact PEP can be found by taking the expectation of the unconditional PEP

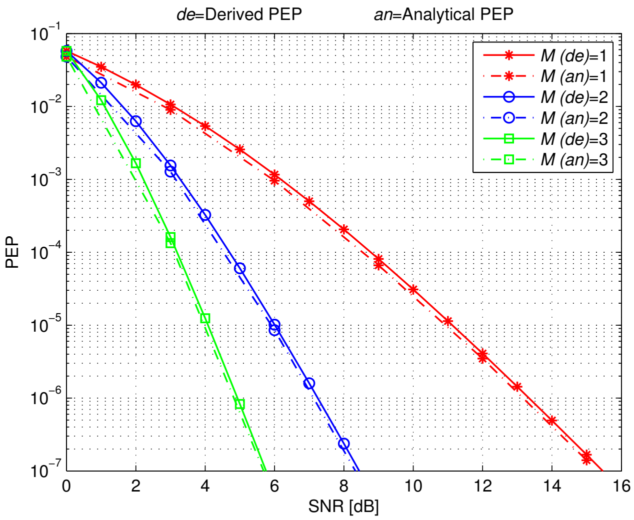

Fig. 2: Derived and analytical PEPs versus SNR.

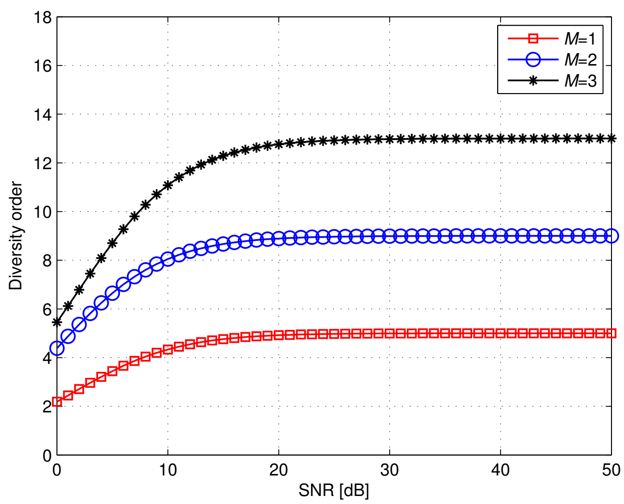

Fig. 3: Diversity order gains with relay selection.

numerically through the random generation of $\mathbf{h}$ with proper statistics. We assume $M = 1,\ 2$ and 3 available relaying vehicles with $[L_{Coop}, Q_{Coop}] = [1, 1]$. We observe that the derived PEP provides a tight upper bound on the exact one with about $\simeq 0.5$dB difference. A power consumption saving is clearly observed, for example at PEP=10^{-5} a transmitting power consumption saving of 5 dB and 7 dB is observed for $M = 2$ and $M = 3$, respectively, with respect to $M = 1$. In Figure 3, we plot the slope of the best-relay selection case PEPs to precisely observe the gain we achieved from our proposed scheme, the achieved asymptotic diversity orders equal to 5, 9 and 13 is observed and consistent with (33).

Acknowledgement

This work was made possible by a *National Priorities Research Program* (NPRP) grant from the Qatar National Research Fund (Member of Qatar Foundation).

V. Conclusion

Existing literature on vehicular relaying for LTE-A networks has mainly focused on networking aspects, but has not yet fully explored physical layer issues, which inherently differ, from the well-studied traditional cellular networks. We have investigated the performance of a cooperative vehicular relaying system over LTE-Advanced downlink sessions, in which eNodeB point communicate to a UE using cooperating vehicles as relaying terminals. For the doubly-selective vehicular channel under consideration, we have employed a precoded cooperative transmission technique to extract the underlying rich multipath-Doppler-spatial diversity. We derived a closed form expression for the pair-wise error probability, as a bench mark to assess our analysis as well as future research studies of such an approach. The analytical and simulation results demonstrated significant performance gains, where notable diversity gains are achieved, as well as notable reduction in the error rates, and a reduction in the transmitting powers compared to the traditional direct transmission is observed.

References

[1] I. K. Fu, Y. S. Chen, P. Cheng, Y. Yuk, R. Yongho Kim and J. S. Kwak, "Multicarrier technology for 4G WiMax system [WiMAX/LTE Update]," *IEEE Commun. Mag.*, vol. 48, pp. 50-58, 2010.

[2] C. Zhang, S. Ariyavisitakul and M. Tao, "LTE-advanced and 4G wireless communications [Guest Editorial]," *IEEE Commun. Mag.*, vol. 50, pp. 102-103, 2012.

[3] M. F. Feteiha and M. Uysal ,"Cooperative Transmission for Broadband Vehicular Networks over Doubly-Selective Fading Channels," *J. IET Commun.*, no 16, pp 1-9, Nov 2012.

[4] M. F. Feteiha and M. Uysal., "Multipath-doppler diversity for broadband cooperative vehicular communications," *in IEEE Int. Conf. Commun.*, ICC'2011, Kyoto, Japan, Jun. 2011, pp. 1-6.

[5] F. Dressler, F. Kargl, J. Ott, O. K. Tonguz and L. Wischof, "Research Challenges in Intervehicular Communication: Lessons of the 2010 Dagstuhl Seminar," *IEEE Commun. Mag.*, vol. 49, pp. 158-164, 2011.

[6] M. Jerbi, S. M. Senouci, Y. Ghamri-Doudane and M. Cherif, "Vehicular Communications Networks: Current Trends and Challenges," *Handbook of Research on Next Generation Mobile Networks and Ubiquitous Computing*, pp. 251 -262, 2012.

[7] J. Laneman, D. Tse and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062-3080, Jun 2004.

[8] X. Ma and G. Giannakis, "Maximum-diversity transmissions over doubly selective wireless channels," *IEEE Trans. Inf. Theory*, vol. 49, pp. 1832-1840, 2003.

[9] Y. Ma, N. Yi and R. Tafazolli, "Bit and power loading for OFDM-based three-node relaying communications," *IEEE Trans. Signal Process.*, vol. 56, pp. 3236-3247, 2008.

[10] S. Ikki and M. Ahmed, "Performance analysis of adaptive decode-and-forward cooperative diversity networks with best-relay selection," *IEEE Trans. Commun.*, Vol. 58, no. 1, pp. 68-72, Jan 2010.

[11] V. Tarokh, N. Seshadri and A. Calderbank, "Space-time codes for high data rate wireless communication: Performance criterion and code construction," *IEEE Trans. Inf. Theory*, vol. 44, pp. 744-765, 1998.

[12] M. Wu, X. Lin and P. Y. Kam, "New exponential lower bounds on the gaussian Q-function via jensen's inequality," in *IEEE 73rd Veh. Technol. Conf.*, VTC'11, Budapest, Hungary, pp. 1-5, May 2011.

[13] H. Muhaidat and M. Uysal, "Cooperative Diversity with Multiple-Antenna Nodes in Fading Relay Channels," *IEEE Trans. Wireless Commun.*, vol. 7, pp. 3036-3046, 2008.

[14] H. Shao and N. C. Beaulieu, "Block coding for impulsive laplacian noise," in *IEEE Int. Conf. Commun.*, ICC'10, Cape Town, South Africa, 2010, pp. 1-6.

[15] M. Ulrey, B. Co and W. Bellevue, "Formulas for the distribution of sums of independent exponential random variables," *IEEE Trans. Reliab.*, vol. 52, no. 2, pp. 154-161, July 2003.

[16] S. M. Ross, *Introduction to Probability and Statistics for Engineers and Scientists*, 3rd ed., California, USA: Elsevier Academic Pr., 2004.

[17] I. Sen and D. Matolak, "V2V channels and performance of multi-user spread spectrum modulation," in *IEEE 66th Vehicular Technology Conf.*, VTC, 2007, pp. 2139-2143.

[18] C. Liu, "The essence of the generalized Newton binomial theorem," Communications in Nonlinear Science and Numerical Simulation, vol. 15, pp. 2766-2768, 2010.