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Transmission success probability analysis of vehicle users with mobile relays under mobility models

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Dear editor,
Mobile relays have been proposed to solve the challenges of capacity boost, coverage extension, and group mobility in the long-term-evolution advanced standard (LTE-A) [1]. A mobile relay inside a public vehicle can receive signals from an eNodeB via external antennas and forward the signals to vehicle user equipments (VUEs) through an internal antenna in the public vehicle. Because public vehicles are usually well shielded with coated windows, VUEs communicate directly with an eNodeB experience poor network services owing to high vehicular penetration loss (VPL) [2]. Installing a mobile relay inside a public vehicle could effectively eliminate the influence of VPL [2]. In addition, mobile relays can utilize the maximal-ratio combining (MRC) technique to improve the spectral efficiency of VUEs [3].

Motivated by the above discussion, this study considers multi-antenna mobile relays that experience interference from other base stations (BSs) with random spatial distribution. Herein, we theoretically study the joint effect of mobile relays, diversity combining techniques, and heterogeneous cellular networks with respect to the transmission success probability of VUEs. First, based on the theory of stochastic geometry, we analyze the transmission success probabilities of a typical VUE under the direct and relay strategies, wherein we explicitly consider spatial interference, MRC techniques, and Nakagami fading channels. Given the location of a public vehicle, we derive the closed-form expressions for the transmission success probabilities of the typical VUE and present the corresponding simulation results that validate the accuracy of the analytical expressions. Second, we analyze the ergodic transmission success probabilities of the typical VUE under the random walk (RW) and random waypoint (RWP) models. In particular, we derive the closed-form expressions for the ergodic transmission success probabilities of the typical VUE in the noise-limited and interference-limited regimes.

System model. In this study, we consider a macro-cell network experiencing interference from K different tiers of interfering BSs. Mobile relays are installed inside public vehicles moving randomly within a finite disk $\mathbb{D}$ of radius D and centered at eNodeB. The public vehicles move along paths characterized by typical mobility models such as the RW and RWP models. At each single-snapshot, let d be the distance between eNodeB and a public vehicle, wherein the distribution of d follows the mobility models. eNodeB can communicate with VUEs through the direct or the relay strategies. In the direct strategy, the single-antenna eNodeB directly communicates with a typical single-antenna VUE. In the relay strategy, an L-antenna mobile relay on the public vehicle's roof decodes data packets from eNodeB and forwards the data packets to the typical VUE through the antenna inside the public vehicle. In addition, the locations of kth-tier interfering BSs follow a Poisson point process Φ_k of density λ_k

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(e.g., in units of BSs per km^2).

Let us consider a transmitter j and receiver u, where $j = B$ for eNodeB; $j = R$ for the mobile relay; $j = ky$ for a kth-tier BS located at $y \in \mathbb{R}^2$; $u = R$ for the mobile relay; and $u = V$ for the typical VUE. Let P_j denote the transmission power of transmitter j. $d_{j,u}$ is the distance between the transmitter j and receiver u. α is the path loss exponent with $\alpha > 2$. $X^l_{j,u}$ is the channel fading component, and ξ is the VPL component. Therefore, the received powers of the typical VUE from eNodeB and the mobile relay are $P_{B,V} = P_B d^{-\alpha}_{B,V} X_{B,V}\xi$ and $P_{R,V} = P_R d^{-\alpha}_{R,V} X_{R,V}$, respectively. Further, the received power of the mobile relay at the lth antenna is $P^l_{B,R} = P_B d^{-\alpha}_{B,R} X^l_{B,R}$.

Herein, we consider independent Nakagami block fading across all channels. m_B is the Nakagami fading parameter of both the B-R and B-V links, m_R is the Nakagami fading parameter of the R-V links, and m_I is the Nakagami fading parameter of the links from interfering BSs to both the mobile relay and typical VUE. Let $f_{X^l_{j,u}}(x)$ be the probability density function of $X^l_{j,u}$ with

$$f_{X^l_{j,u}}(x) = \frac{m_j^{m_j} x^{m_j-1}}{\Gamma(m_j)} \exp(-m_j x),\ x \geqslant 0.$$

The signal-to-interference-plus-noise ratio (SINR) with MRC under a full-correlation model is obtained in [4] as $\mathrm{SINR}_{j,u}(d) = \frac{\sum_{l=1}^{L} P_j d^{-\alpha}_{j,u} X^l_{j,u}\xi_{j,u}}{I+N_0}$, where $I = \sum_{k=1}^{K}\sum_{y_i\in\Phi_k} P_{ky}\|y_i\|^{-\alpha} X_{ky,u}\xi_{ky,u}$ is the interference power experienced at the receiver u, and N_0 is the noise power. According to the modified Shannon capacity [5], the spectral efficiency between the transmitter j and the receiver u is $\mathcal{R}_{j,u}(d) = \eta_{\mathrm{BW}} \log_2(1 + \frac{\mathrm{SINR}_{j,u}(d)}{\eta_{\mathrm{SINR}}})$, where η_{BW} and η_{SINR} are the modification factors. The link spectral efficiency $\mathcal{R}_{\mathrm{RS}}$ of the relay strategy is $\mathcal{R}_{\mathrm{RS}}(d) = \frac{1}{2}\min\{\mathcal{R}_{\mathrm{B,R}}(d), \mathcal{R}_{\mathrm{R,V}}(d)\}$, which is obtained by applying the half-duplex decode-and-forward cooperation protocol. Furthermore, transmission success probability is defined as the probability in which the link spectral efficiency $\mathcal{R}_{\mathrm{DS}}$ (respectively $\mathcal{R}_{\mathrm{RS}}$) of the direct (respectively relay) strategy exceeds a target spectral efficiency $\mathcal{R}_{\mathrm{th}}$; the transmission success probability is shown as $\mathcal{P}_{\mathrm{DS}}(\mathcal{R}_{\mathrm{th}}, d) = \Pr(\mathrm{SINR}_{\mathrm{B,V}}(d) \geqslant \beta_{\mathrm{B,V}})$ (respectively $\mathcal{P}_{\mathrm{RS}}(\mathcal{R}_{\mathrm{th}}, d) = \Pr(\mathrm{SINR}_{\mathrm{B,R}}(d) \geqslant \beta_{\mathrm{B,R}}) \times \Pr(\mathrm{SINR}_{\mathrm{R,V}}(d_{\mathrm{R,V}}) \geqslant \beta_{\mathrm{R,V}})$), where $\beta_{\mathrm{B,V}} = \eta_{\mathrm{SINR}}(2^{\frac{\mathcal{R}_{\mathrm{th}}}{\eta_{\mathrm{BW}}}} - 1)$ for the B-V links, $\beta_{\mathrm{B,R}} = \beta_{\mathrm{R,V}} = \eta_{\mathrm{SINR}}(2^{\frac{2\mathcal{R}_{\mathrm{th}}}{\eta_{\mathrm{BW}}}} - 1)$ for the B-R and R-V links, and $d_{R,V}$ denotes the distance between the mobile relay and typical VUE.

Single snapshot analysis of transmission success probability. In this section, we focus on a single snapshot of the network, i.e., the location of the public vehicle is stationary in a short-term frame. Accordingly, we obtain the following proposition.

Proposition 1. For a single snapshot of the network, the transmission success probabilities of the direct link (B $\leftrightarrow$ V), the backhaul link (B $\leftrightarrow$ R), and the access link (R $\leftrightarrow$ V) for the typical VUE are given as follows:

$$\mathcal{P}_{\mathrm{B,V}}(\mathcal{R}_{\mathrm{th}}, d) = \sum_{n=0}^{m_{\mathrm{B}}-1} \frac{\partial^n}{\partial s^n}\left[\exp\left(- \frac{s m_{\mathrm{B}}\beta_{\mathrm{B,V}} N_0}{P_{\mathrm{B}} d^{-\alpha}\xi} - \sum_{k=1}^{K} \pi\psi_k d^2 s^{\frac{2}{\alpha}} \left(\frac{\beta_{\mathrm{B,V}} m_{\mathrm{B}}}{P_{\mathrm{B}}}\right)^{\frac{2}{\alpha}}\right)\right]_{s=1} \frac{(-1)^n}{n!}, \quad (1)$$

$$\mathcal{P}_{\mathrm{B,R}}(\mathcal{R}_{\mathrm{th}}, d) = \sum_{n=0}^{Lm_{\mathrm{B}}-1} \frac{\partial^n}{\partial s^n}\left[\exp\left(- \frac{s m_{\mathrm{B}}\beta_{\mathrm{B,R}} N_0}{P_{\mathrm{B}} d^{-\alpha}} - \sum_{k=1}^{K} \pi\psi_k d^2 s^{\frac{2}{\alpha}} \left(\frac{\beta_{\mathrm{B,R}} m_{\mathrm{B}}}{P_{\mathrm{B}}}\right)^{\frac{2}{\alpha}}\right)\right]_{s=1} \frac{(-1)^n}{n!}, \quad (2)$$

$$\mathcal{P}_{\mathrm{R,V}}(\mathcal{R}_{\mathrm{th}}) = \sum_{n=0}^{m_{\mathrm{R}}-1} \frac{\partial^n}{\partial s^n}\left[\exp\left(- \frac{s m_{\mathrm{R}}\beta_{\mathrm{R,V}} N_0}{P_{\mathrm{R}} d^{-\alpha}_{\mathrm{R,V}}} - \sum_{k=1}^{K} \pi\psi_k s^{\frac{2}{\alpha}} \left(\frac{\beta_{\mathrm{R,V}} m_{\mathrm{R}}\xi}{P_{\mathrm{R}}}\right)^{\frac{2}{\alpha}}\right)\right]_{s=1} \frac{(-1)^n}{n!}, \quad (3)$$

where $\psi_k = \lambda_k(\frac{P_k}{m_{\mathrm{I}}})^{\frac{2}{\alpha}} \frac{\Gamma(1-\frac{2}{\alpha})\Gamma(\frac{2}{\alpha}+m_{\mathrm{I}})}{\Gamma(m_{\mathrm{I}})}$.

Proof. Refer to Appendix A.

Ergodic transmission success probability. We extend the single snapshot analysis of the typical VUE to the ergodic transmission success probabilities under the RW and RWP models. In the RW model, the public vehicle randomly chooses a direction and speed in each time period; therefore, the spatial distribution of the public vehicle is uniform [6], i.e., $f^{\mathrm{RW}}_{\mathrm{D}}(d) = \frac{2d}{D^2}$, $0 \leqslant d \leqslant D$. In the RWP model, the public vehicle uniformly selects a destination within the region $\mathbb{D}$ and moves toward it with a constant speed; thus, the spatial distribution of the public vehicle is nonuniform [6], i.e., $f^{\mathrm{RWP}}_{\mathrm{D}}(d) = \frac{4d}{D^2} - \frac{4d^3}{D^4}$, $0 \leqslant d \leqslant D$. For analytical tractability, we classified the ergodic transmission success probability of the typical VUE into noise-limited and interference-limited regimes. Accordingly, the following propositions were developed.

Proposition 2. The ergodic transmission success probabilities of the typical VUE in the noise-limited regime are given as follows: $\mathcal{P}^{\mathrm{RW}}_{\mathrm{DS}}(\mathcal{R}_{\mathrm{th}}) = \sum_{n=0}^{m_{\mathrm{B}}-1} \frac{2/\alpha}{n!D^2}(\frac{\xi}{\beta_{\mathrm{B,V}}\kappa})^{\frac{2}{\alpha}} \times \gamma(n + \frac{2}{\alpha}, \frac{\beta_{\mathrm{B,V}}\kappa}{D^{-\alpha}\xi})$, $\mathcal{P}^{\mathrm{RW}}_{\mathrm{RS}}(\mathcal{R}_{\mathrm{th}}) = [\sum_{n=0}^{Lm_{\mathrm{B}}-1} \frac{2/\alpha}{n!D^2}(\frac{1}{\beta_{\mathrm{B,R}}\kappa})^{\frac{2}{\alpha}} \times \gamma(n + \frac{2}{\alpha}, \frac{\beta_{\mathrm{B,R}}\kappa}{D^{-\alpha}})] \cdot \mathcal{P}_{\mathrm{R,V}}(\mathcal{R}_{\mathrm{th}})$, $\mathcal{P}^{\mathrm{RWP}}_{\mathrm{DS}}(\mathcal{R}_{\mathrm{th}}) = \sum_{n=0}^{m_{\mathrm{B}}-1} \frac{4/\alpha}{n!D^2}[(\frac{\xi}{\beta_{\mathrm{B,V}}\kappa})^{\frac{2}{\alpha}} \times \gamma(n + \frac{2}{\alpha}, \frac{\beta_{\mathrm{B,V}}\kappa}{D^{-\alpha}\xi}) - \frac{1}{D^2}(\frac{\xi}{\beta_{\mathrm{B,V}}\kappa})^{\frac{4}{\alpha}} \times \gamma(n + \frac{4}{\alpha}, \frac{\beta_{\mathrm{B,V}}\kappa}{D^{-\alpha}\xi})]$, $\mathcal{P}^{\mathrm{RWP}}_{\mathrm{RS}}(\mathcal{R}_{\mathrm{th}}) =$

$\mathcal{P}_{\rm R,V}(\mathcal{R}_{\rm th})\sum_{n=0}^{Lm_{\rm B}-1}\frac{4/\alpha}{n!D^2}[(\frac{1}{\beta_{\rm B,R}\kappa})^{\frac{2}{\alpha}}\times\gamma(n+\frac{2}{\alpha},\frac{\beta_{\rm B,R}\kappa}{D^{-\alpha}})-\frac{1}{D^2}(\frac{1}{\beta_{\rm B,R}\kappa})^{\frac{4}{\alpha}}\times\gamma(n+\frac{4}{\alpha},\frac{\beta_{\rm B,R}\kappa}{D^{-\alpha}})]$, where $\kappa=\frac{m_{\rm B}N_0}{P_{\rm B}}$.

Proof. Refer to Appendix B.

Proposition 3. The ergodic transmission success probabilities of the typical VUE in the interference-limited regime are given as follows:

$$\mathcal{P}_{\rm DS}^{\rm RW}(\mathcal{R}_{\rm th})=\sum_{n=0}^{m_{\rm B}-1}\frac{(-1)^n}{n!}\frac{\partial^n}{\partial s^n}\times\left[\frac{1-\exp(-s^{\frac{2}{\alpha}}\beta_{\rm B,V}^{\frac{2}{\alpha}}\zeta)}{s^{\frac{2}{\alpha}}\beta_{\rm B,V}^{\frac{2}{\alpha}}\zeta}\right]_{s=1},\quad(4)$$

$$\mathcal{P}_{\rm RS}^{\rm RW}(\mathcal{R}_{\rm th})=\mathcal{P}_{\rm R,V}(\mathcal{R}_{\rm th})\sum_{n=0}^{Lm_{\rm B}-1}\frac{(-1)^n}{n!}\frac{\partial^n}{\partial s^n}\times\left[\frac{1-\exp(-s^{\frac{2}{\alpha}}\beta_{\rm B,R}^{\frac{2}{\alpha}}\zeta)}{s^{\frac{2}{\alpha}}\beta_{\rm B,R}^{\frac{2}{\alpha}}\zeta}\right]_{s=1},\quad(5)$$

$$\mathcal{P}_{\rm DS}^{\rm RWP}(\mathcal{R}_{\rm th})=\sum_{n=0}^{m_{\rm B}-1}\frac{(-1)^n}{n!}\frac{\partial^n}{\partial s^n}\left[\frac{2}{s^{\frac{2}{\alpha}}\beta_{\rm B,V}^{\frac{2}{\alpha}}\zeta}+\frac{2\exp(-s^{\frac{2}{\alpha}}\beta_{\rm B,V}^{\frac{2}{\alpha}}\zeta)-2}{(s^{\frac{2}{\alpha}}\beta_{\rm B,V}^{\frac{2}{\alpha}}\zeta)^2}\right]_{s=1},\quad(6)$$

$$\mathcal{P}_{\rm RS}^{\rm RWP}(\mathcal{R}_{\rm th})=\mathcal{P}_{\rm R,V}(\mathcal{R}_{\rm th})\cdot\left(\sum_{n=0}^{Lm_{\rm B}-1}\frac{(-1)^n}{n!}\times\frac{\partial^n}{\partial s^n}\left[\frac{2\exp(-s^{\frac{2}{\alpha}}\beta_{\rm B,R}^{\frac{2}{\alpha}}\zeta)-2}{(s^{\frac{2}{\alpha}}\beta_{\rm B,R}^{\frac{2}{\alpha}}\zeta)^2}+\frac{2}{s^{\frac{2}{\alpha}}\beta_{\rm B,R}^{\frac{2}{\alpha}}\zeta}\right]_{s=1}\right),\quad(7)$$

where $\zeta=D^2(\frac{m_{\rm B}}{P_{\rm B}})^{\frac{2}{\alpha}}(\sum_{k=1}^{K}\pi\psi_k)$.

Proof. Refer to Appendix C.

Simulation results. Herein, we present the transmission success probabilities of both direct and relay strategies vs. the distance between eNodeB and the public vehicle under different densities of interfering BSs in Figure 1. Appendix D contains values of partial parameters. Analytical and numerical results are denoted by lines and markers, respectively. The numerical results validated the analytical results. In addition, the simulation results of the ergodic transmission success probabilities are provided in Appendix E. Furthermore, these analytical expressions on the transmission success probabilities of the typical VUE can be applied to design strategy selection algorithms, as shown in Appendix F.

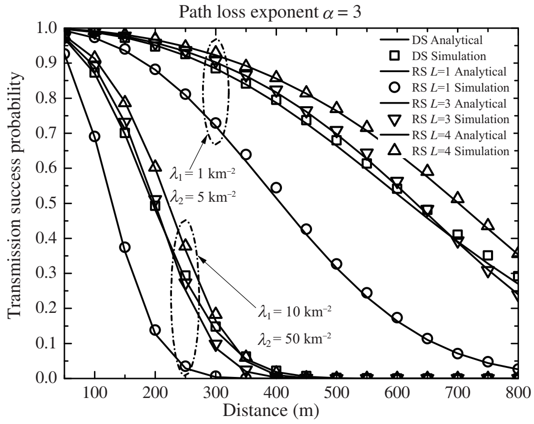

Figure 1 Transmission success probability vs. distance d between eNodeB and the public vehicle, with $m_{\rm B}=m_{\rm R}=m_{\rm I}=2$, $\xi=-25$ dB, $\alpha=3$, and $\mathcal{R}_{\rm th}=1$ bps/Hz.

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Supporting information Appendixes A–F. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 3GPP. Mobile relay for E-UTRA. Technical report, TR 36.836. 2012
2 Sui Y T, Papadogiannis A, Yang W, et al. Performance comparison of fixed and moving relays under co-channel interference. In: Proceedings of IEEE Globecom Workshops, California, 2012. 574–579
3 Sui Y T, Vihriala J, Papadogiannis A, et al. Moving cells: a promising solution to boost performance for vehicular users. IEEE Commun Mag, 2013, 51: 62–68
4 Tanbourgi R, Dhillon H S, Andrews J G, et al. Dual-branch MRC receivers under spatial interference correlation and nakagami fading. IEEE Trans Commun, 2014, 62: 1830–1844
5 Mogensen P, Na W, Kovacs I Z, et al. LTE capacity compared to the shannon bound. In: Proceedings of IEEE 65th Vehicular Technology Conference, Dublin, 2007. 1234–1238
6 Bandyopadhyay S, Coyle E J, Falck T. Stochastic properties of mobility models in mobile Ad Hoc networks. IEEE Trans Mobile Comput, 2007, 6: 1218–1229