Context-Aware Handover Optimization for Relay-Aided Vehicular Terminals

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***Abstract*—The handover (HO) performance of a user in wireless cellular networks depends on HO parameters and context such as user position and velocity. We propose a novel HO optimization approach for high-mobility users aided by vehicle-mounted relay. By exploiting the learned or predicted context information obtained at the relay, we derive closed-form expressions of outage probabilities related to the events of too-early and too-late HO. We show that a good trade-off between minimization of HO-related radio link failures and reduction of unnecessary HOs can be achieved by minimizing the weighted sum of the above mentioned outage probabilities. The proposed algorithm, evaluated by numerical simulations, turns out to outperform conventional HO optimization strategies for a wide range of user velocities.**

I. Introduction

Mobility robustness optimization (MRO) [1], introduced as one use case of self-organizing networks (SON), refers to procedures for automated setting of HO parameters aimed at minimizing HO-related radio link failures (RLFs) and reducing the number of unnecessary or missed HOs. Conventional MRO algorithms (see, for example, [2]–[4]) operate on a cell level, i.e., optimize the HO parameters based on the dominant class of users in a cell. However, the HO performance and requirements of individual users may be different, depending on the users' mobility state, trajectory, and other context variables. Therefore, when available, mobility and context information can be exploited to design more effective, user-specific MRO algorithms. This is the case, for example, of vehicular terminals (VTs) serving as mobile relays, where the vehicle speed and trajectory can be assumed as known or predictable with reasonable confidence level. Previous results in this scenario were presented in [5], where we proposed a street-specific HO optimization algorithm for VTs based on upper bounds of the HO metrics. In this paper we provide the following contributions:

- We derive novel closed-form expressions of outage probabilities related to the events of too-early and too-late HO, taking the statistical fading distribution into account.
- We show that the objective function based on the above closed-form expressions reflects the properties of the desired HO performance metrics.
- The analytical solution provides an efficient one-step optimization, and it works for various user profiles, including in particular different mobility states.

The paper is organized as follows: in Section II we describe the system model, introducing the relevant context information, HO parameters and performance metrics; in Section III we derive the analytical expressions for HO-related outage probabilities; we then formulate the HO optimization problem and provide an algorithmic solution in Section IV; simulation results are presented in Section V; conclusion and further discussions are provided in Section VI.

II. System model

A. Received signal at VTs

Consider a group of users in a vehicle communicating with the base station (BS) through a VT, with negligible penetration loss and ideal error-free transmission thanks to the presence of access link antennas inside the vehicle. A VT receives reference signals from a set of BSs $\mathcal{N}$ with cardinality N. The *reference signal received power* (RSRP) from BS n is given by $R_n = P_n l_n h_n$, where P_n denotes the *reference signal transmit power* of BS n (known at the VT), $l_n := (G_n G_0 \lambda^2)/(4\pi d_n)^2$ is the path-loss gain (depending on the transmit antenna gain G_n, receive antenna gain G_0, signal wavelength λ and distance between the BS n and the user d_n), and h_n denotes the fast-fading channel gain. Assume that the fading is Rayleigh distributed, i.e., $h_n = \alpha_n^2$, where $\alpha_n \sim f_{\alpha_n}(\alpha_n) = (2\alpha_n/A_n)\exp\left(-\alpha_n^2/A_n\right)$, with $E[\alpha_n^2] := A_n$. Thus, the random variable (r.v.) h_n follows an exponential distribution $f(h_n;\lambda_n) := \lambda_n \exp\left(-\lambda_n h_n\right)$, with rate parameter $\lambda_n = 1/A_n$ [6].

Assume the interference seen by a user in LTE systems is averaged over resource blocks, which can be achieved by frequency hopping [7], this simplifies the *signal-to-interference-plus-noise ratio* (SINR) model depending on the allocated bandwidth:

$$\gamma_n = \frac{P_n l_n h_n}{\omega_n \sum_{\substack{i=1\\ i\neq n}}^{N} P_i l_i h_i + \omega_n \sigma^2} = \frac{R_n}{\omega_n \sum_{\substack{i=1\\ i\neq n}}^{N} R_i + \omega_n \sigma^2}, \quad (1)$$

where $\omega_n \in [0,1]$ is a fraction of the allocated bandwidth and σ^2 denotes the variance of the noise at the receiver. It follows from (1) that the SINR can be estimated from the measured RSRPs. The RSRP R_n is a r.v. depending on the constant values P_n, l_n, and an exponential r.v. h_n. Thus, the SINR can be seen as a ratio of an exponential r.v. to a sum of independent exponential r.v.s (with different means) and

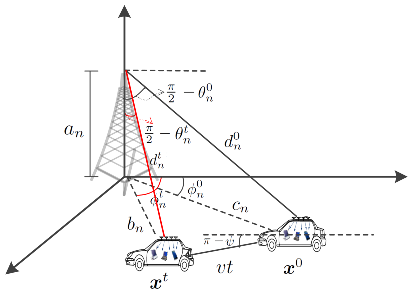


Fig. 1. Problem geometry.

the constant noise variance. The distribution of the SINR r.v. depends on the unknown parameters l_n (path-loss) and A_n (mean value of h_n), which can be learned exploiting context information as stated in Subsection II-B.

B. *Path-loss and fading prediction using context information*

Assume that a VT can estimate (at the current time) and predict (in the short-term future) its speed v, location, and trajectory (a sequence of positions $\boldsymbol{x}^0, \ldots, \boldsymbol{x}^t$ and horizontal relative moving angle ψ), by using GPS data. In addition, assume that the VT knows the position ($\boldsymbol{x}^0$), height (a_n), and antenna downtilt and azimuth $(\hat{\vartheta}_n, \hat{\varphi}_n)$ of the current as well as the neighboring BSs. Thanks to this information, the path-loss coefficient at time t (l_n^t) can be calculated as a function of the distance d_n^t and the antenna gain G_n^t, which in turn depends on the difference between the antenna downtilt and the elevation-of-arrival $(\hat{\vartheta}_n - \theta_n^t)$ and the difference between the antenna azimuth and the azimuth-of-arrival $(\hat{\varphi}_n - \phi_n^t)$. With reference to Fig. 1, the unknown parameters $\phi_n^t, \theta_n^t, d_n^t$ can be derived as

$$\phi_n^t = \phi_n^0 + \arccos\left(\frac{b_n^2 + c_n^2 - (vt)^2}{2b_n c_n}\right) \tag{2}$$

$$\theta_n^t = \arctan\left(\frac{a_n}{b_n}\right);\ d_n^t = \sqrt{a_n^2 + b_n^2} \tag{3}$$

$$\text{where } b_n = \sqrt{(vt)^2 + c_n^2 + 2vtc_n\cos(\phi_n^0 - \psi)}$$
$$c_n = d_n^0 \cos\theta_n^0.$$

Once l_n^t is estimated, samples of h_n can be extracted from K previous RSRP measurements $R_n^k = P_n^k l_n^k h_n^k$ with $k \in \{t - k_0 - K, t - k_0 - 1\}$, $k_0, K \in \mathbb{N}$ (we recall that P_n^k is known). Assuming that the samples h_n^k are i.i.d. within the considered sampling period, the unknown parameter A_n (constant during the sampling period) can be estimated by maximum likelihood as the sample average $\frac{1}{K}\sum_{k=t-k_0-K}^{t-k_0-1} h_n^k$ and used as an estimate of A_n^t in the current time slot t.

C. *HO process and parameters*

A HO process from BS n to BS m starts with *Event A3* [8], defined as a triggering event if the condition $R_m/R_n \geq M$ is satisfied, where M is the *handover margin* (HOM) in linear scale. If the condition holds for a time T called *time to trigger* (TTT), a *handover request* (HRQ) is sent to BS m. Notice that in a conventional HO mechanism the HOM is defined for a cell pair $M := M_{n,m}$ while the TTT is cell-specific $T := T_n$. In our approach, both HO parameters are VT-specific, such that (M, T) are optimized per VT to adapt to the time-variant local context information. An HRQ is considered successful if, after sending the request, the vehicle moves into a coverage area of cell m (a region where $\Pr\left(\gamma_m \leq \gamma^{th}\right) \leq \eta$ is satisfied for some predefined thresholds γ^{th} and η); otherwise we have a *too-early HO-related radio link failure* (E_RLF). In contrast, a *too-late HO-related radio link failure* (L_RLF) happens if the vehicle leaves the coverage area of the serving cell before a successful HO is completed. Finally, a *ping-pong HO* (PPH) is defined to be a HO event to a neighbor cell that returns to the source cell after a short time T_{CRIT}.

D. *HO performance metrics*

The HO performance is usually evaluated by three HO metrics: too-early HO-related radio link failure ratio (E_RLFR), too-late HO-related radio link failure ratio (L_RLFR), and ping-pong HO ratio (PPHR) [1]. We aim at minimizing HO-related RLFs implied by E_RLFR and L_RLFR, as well as the number of unnecessary HOs implied by PPHR. However, minimizing L_RLFR and (E_RLFR, PPHR) are contradicting objectives. The former (reduction of too-late HO decisions) requires either to enter the A3 event sooner, i.e., decreasing M, or to shorten the waiting time T, whereas the latter (reduction of too-early HO decisions) requires to increase M or T. Thus, optimizing the HO performance means finding an appropriate trade-off between too-early and too-late HO decisions.

III. HO-RELATED OUTAGE PROBABILITIES

A. *Channel outage probability*

The analytical expression of channel outage probability is derived from the following result. Suppose $X_1, \ldots, X_N$ are independent exponentially distributed r.v.s with density functions $f(X_i; \lambda_i)$ and means $E[X_i] = 1/\lambda_i, i = 1, \ldots, N$. Then, we have [9]

$$\Pr\left(X_1 \leq \sum_{i=2}^{N} X_i\right) = 1 - \prod_{i=2}^{N}\left(\frac{1}{1 + \frac{\lambda_1}{\lambda_i}}\right). \tag{4}$$

By introducing a constant c, (4) is modified as

$$\Pr\left(X_1 \leq \sum_{i=2}^{N} X_i + c\right) = 1 - \exp\left(-\lambda_1 c\right)\prod_{i=2}^{N}\left(\frac{1}{1 + \frac{\lambda_1}{\lambda_i}}\right). \tag{5}$$

Knowing that the exponential distribution is closed under scaling by a positive factor, the RSRP $R_i^t = P_i^t l_i^t \cdot h_i^t$ is exponentially distributed with rate parameter

$$\beta_i^t = \lambda_i^t / P_i^t l_i^t = 1/P_i^t l_i^t A_i^t = 1/E[R_i^t]. \tag{6}$$

With (5) we can easily obtain the outage probability of the channel between BS i and the user at time t as

$$O_i^t = \Pr\left(\gamma_i^t \leq \gamma^{th}\right) = \Pr\left(\frac{1}{\omega_i^t \gamma^{th}} R_i^t \leq \sum_{\substack{j=1 \\ j \neq i}}^{N} R_j^t + \sigma^2\right)$$
$$= 1 - \exp\left(-\omega_i^t \gamma^{th} \beta_i^t \sigma^2\right) \prod_{\substack{j=1 \\ j \neq i}}^{N}\left(\frac{1}{1 + \frac{\beta_i^t}{\beta_j^t}\omega_i^t \gamma^{th}}\right). \tag{7}$$

B. Probability mass function of time slot of handover

Let t_{HO} denote the time slot of handover. Consider a user who has not started the HO process from BS n to BS m up to the current time slot t_0. Recall that a HO event from BS n to BS m is triggered after the condition $R_m^t/R_n^t \geq M$ holds for a time T, and the HO action is accomplished after the HRQ is accepted. The time slot of handover can be seen as the first hit time of a sequence of events $\{R_m^t/R_n^t \geq M : t = t_{HO} - T + 1, \ldots, t_{HO}\}$. The probability that a HO event happens at time $t > t_0, t \in \mathbb{Z}$, denoted by $H_{n\to m}^t$, depends on the following three events

$$\mathrm{E}_1^t := \bigcap_{\tau=t-T+1}^{t} \left\{ \frac{R_m^\tau}{R_n^\tau} \geq M \right\} \text{ if } t \geq t_0 + T \tag{8}$$

$$\mathrm{E}_2^t := \left\{ \frac{R_m^{t-T}}{R_n^{t-T}} < M \right\} \text{ if } t > t_0 + T \tag{9}$$

$$\mathrm{E}_3^t := \bigcap_{\tau=t_0+T}^{t-T-1} \overline{\mathrm{E}_1^\tau} \text{ if } t > t_0 + 2T \tag{10}$$

where $\tau \in \mathbb{Z}$ and $\overline{\mathrm{E}_1}$ denotes the complement of event E_1. More specifically, the event E_1^t in (8) occurs when the HO criterion holds for time period $[t - T + 1, t]$ (T slots); the event E_2^t in (9) happens when the HO criterion does not hold at time $(t - T)$, while the event E_3^t occurs when the user has not been handed over till time $(t - T - 1)$. It is assumed that the HO process has not started up to current time t_0. Thus, we have $\mathrm{E}_1^t | t < t_0 + T := \emptyset$, $\mathrm{E}_2^t | t \leq t_0 + T := U$ and $\mathrm{E}_3^t | t \leq t_0 + 2T := U$, where U denotes the universal set, and $H_{n\to m}^t, t > t_0, t \in \mathbb{Z}$ can be written as

$$H_{n\to m}^t = \Pr\left(\mathrm{E}_1^t \cap \mathrm{E}_2^t \cap \mathrm{E}_3^t\right) \text{ if } t \geq t_0 + T \tag{11}$$

For $t < t_0 + T$, we define $H_{n\to m}^t := 0$.

Now assume a block-fading model [10] where the fading coefficients are constant over a time slot and vary independently from slot to slot. Then, (11) becomes simply the product of $\Pr(E_1^t)$, $\Pr(E_2^t)$, and $\Pr(E_3^t)$, i.e., for $t \geq t_0 + T, t \in \mathbb{Z}$, we have

$$H_{n\to m}^t = \left(\prod_{\nu=t-T+1}^{t} C_{n\to m}^\nu \right) \cdot \left(1 - C_{n\to m}^{t-T}\right) \cdot V_{n\to m}^t. \tag{12}$$

Note that $C_{n\to m}^t$ is the probability that the HO condition $R_m^t/R_n^t \geq M$ is satisfied at time slot t and is derived using (4) to yield

$$C_{n\to m}^t = \Pr\left(\frac{R_m^t}{R_n^t} \geq M \right) = \begin{cases} \frac{1}{1+\frac{\beta_m^t}{\beta_n^t}M} & \text{if } t > t_0 \\ 0 & \text{o.w.} \end{cases}. \tag{13}$$

Since events E_3^t are disjoint for different time slots, $V_{n\to m}^t$ as the probability that the user has not been handed over till time $(t - T - 1)$ can be written as

$$V_{n\to m}^t = \begin{cases} 1 - \sum_{\tau=t_0+T}^{t-T-1} H_{n\to m}^\tau & \text{if } t > t_0 + 2T \\ 1 & \text{o.w.} \end{cases}. \tag{14}$$

We remark that, thanks to the prediction of l_i^t and A_i^t, a VT is able to compute $\beta_i^t = 1/P_i^t l_i^t A_i^t$ for $i \in \mathcal{N}$ and hence $H_{n\to m}^t$ in the near future.

C. Outage probability at the time slot of handover

Consider a user who has not started the HO process from serving BS n to target BS m up to the current time slot t_0. A HO event happens within a time interval $[t_0+1, t_0+K']$ with a probability larger than $1-\epsilon$, where $\epsilon \geq 0$ is an arbitrary small constant, if K' satisfies the following condition

$$K' = \arg\min_K \left\{ K : \sum_{t=t_0+1}^{t_0+K} H_{n\to m}^t \geq 1 - \epsilon \right\}. \tag{15}$$

Since $\sum_{t=t_0+1}^{t_0+K'} H_{n\to m}^t \approx 1$, the vector of $H_{n\to m}^t$ for $t = t_0 + 1, \ldots, t_0 + K'$ approximates the probability mass function of the time slot of handover t_{HO}. Using $P(A) = \sum_i P(A|B_i)P(B_i)$, the outage probability of the channel to BS i at time slot of handover is approximated by

$$O_i^{t_{HO}} \approx \sum_{t=t_0+1}^{t_0+K'} O_i^t H_{n\to m}^t, \text{ for } i \in \mathcal{N}. \tag{16}$$

IV. Problem formulation and Algorithm

The objective is to minimize the number of too-late and too-early HO decisions.[1] Specifically, we formulate our optimization problem so as to minimize *(i)* the worst-case outage probability of the channel between the serving BS n and the user before t_{HO} (too-late related), and *(ii)* the worst-case outage probability of the channel between the target BS m and the user after t_{HO} (too-early related). At time slot t_0, the two contradicting optimization problems are written as

P1. $\min_{M,T} \max_{t\in[t_0+1,t_{\mathrm{HO}}]} O_n^t$
P2. $\min_{M,T} \max_{t\geq t_{\mathrm{HO}}} O_m^t$

Proposition 1: Assume that at time slot t_0, a user in serving BS n chooses the target BS m with maximum average expected RSRP value during $[t_0 + 1, t_0 + L]$, i.e., $m = \arg\max_{i\neq n}(1/L)\sum_{t=t_0+1}^{t_0+L} E[R_i^t]$, where L is a sufficiently large constant but still within the predictability range of the context information. If $E[R_n^t]$ is a monotonic decreasing function of t, and $E[R_m^t]$ is monotonic increasing,[2] then we have

$$t_{\mathrm{HO}} = \arg\max_{t\in[t_0+1,t_{\mathrm{HO}}]} O_n^t = \arg\max_{t\in[t_{\mathrm{HO}},t_0+L]} O_m^t. \tag{17}$$

Proof: The proof is given in the Appendix. ■

Now, a global objective function can be formulated as a weighted sum of the two contradicting objectives, i.e., the outage probabilities related to the events of too-early and too-late HO $O_m^{t_{\mathrm{HO}}}$ and $O_n^{t_{\mathrm{HO}}}$. Therefore, by using the result of Proposition 1, we pose the optimization problem as

$$\min_{M,T} F(M,T) := \alpha_n O_n^{t_{\mathrm{HO}}} + \alpha_m O_m^{t_{\mathrm{HO}}} \quad \text{s.t.} \quad M \in \mathcal{M}, T \in \mathcal{T} \tag{18}$$

where $\mathcal{T}$ and $\mathcal{M}$ are sets of possible values of TTT and HOM, $\alpha_i \geq 0, \sum_{i=n,m} \alpha_i = 1$, and the probabilities $O_n^{t_{\mathrm{HO}}}$, $O_m^{t_{\mathrm{HO}}}$ are computed using (16), (7), (12), (15).

[1] Minimizing the number of too-late HO decisions decreases L_RLFR, while minimizing the number of too-early HO decisions decreases both PPHR and E_RLFR.

[2] Note that $E[R_i^t] = P_i^t l_i^t A_i^t$, this assumption usually holds when the user is detected to be moving away from BS n and towards BS m

Algorithm 1: Vehicle specific MRO algorithm

1: Initiate with $k = 1$, the default values $(H^{(1)}, M^{(1)})$, a small constant $\mu > 0$, $t_k = k \cdot L$, and distance threshold D for choosing candidate target BSs. Optimization decision is made at the last slot t_k of the k-th time period for the $(k+1)$-th time period $[t_k + 1, t_{k+1}]$.
2: **loop**
3: Formulate the neighborhood list $\mathcal{N} = \{i : d_i^{t_k} \le D\}$.
4: Predict context information $P_i^t l_i^t$, A_i^t and compute β_i^t for $i \in \mathcal{N}$, $t \in [t_{k-1} + 1, t_k]$.
5: **if** $n = \arg\max_i (1/L) \sum_{t=t_k+1}^{t_{k+1}} 1/\beta_i^t$ and $O_n^{t_{k+1}} \le \mu$ **then**
6: $(M^{(k+1)}, T^{(k+1)}) \leftarrow (M^{(k)}, T^{(k)})$
7: **else**
8: $m \leftarrow \arg\max_{i \in \mathcal{N} \setminus n} (1/L) \sum_{t=t_k+1}^{t_{k+1}} 1/\beta_i^t$.
9: $(M^{(k+1)}, T^{(k+1)}) \leftarrow$ $\arg\min_{M \in \mathcal{M}, T \in \mathcal{T}} \sum_{i=n,m} \alpha_i O_i^{t_{\text{HO}}}$
10: **end if**
11: $k \leftarrow k + 1$
12: **end loop**

The optimal solution to the combinatorial optimization problem in (18) is difficult to derive, since the objective function is neither convex nor monotone, and the parameters belong to the discrete sets $M \in \mathcal{M}, T \in \mathcal{T}$. However, in practical systems, $\mathcal{M}$ and $\mathcal{T}$ are finite sets with small cardinality, e.g., $|\mathcal{T}| = 14$. An exhaustive search is feasible, and the best combination of (M, T) can be chosen. A practical algorithmic solution is proposed in Algorithm 1. The basic concept is to optimize the HO parameters dynamically based on the predicted future states of $P_i^t l_i^t$ and $A_i^t, \forall i \in \mathcal{N}, t = [t_0 + 1, t_0 + L]$. It is a proactive optimization algorithm, in the sense that HO parameters are optimized periodically to provide a good trade-off between the outage probabilities related to the events of too-early and too-late HO. An exception is made when the average RSRP from the serving BS is good enough to support a low worst-case outage probability (lower than a predefined threshold μ), then the user shall stay in the serving BS and the HO parameters remain the same as in the previous time period. The algorithm can be directly implemented in a VT, since all the information needed to compute the objective function in (18) is β_i^t for $i \in \mathcal{N}$ and $H_{n \to m}^t$ for $t \in [t_0 + 1, t_0 + L]$, which is available at the VT.

V. Simulations

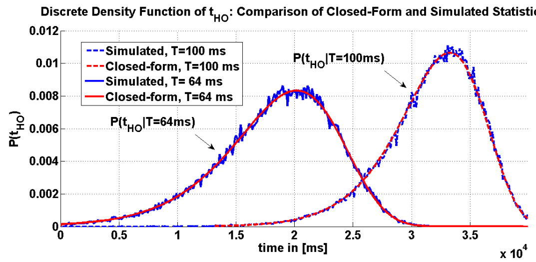
We consider a hexagonal network composed of 7 tri-sectored BSs (one central cell surrounded by six neighboring cells) with site-to-site distance of 2 km. At every run of the simulation (100,000 in total), we simulate 100 users that are initially located in the central cell (with uniform distribution) and then start to move with random directions towards the neighboring cells. The antenna gains G_0 and G_n are modeled according to the urban scenario defined in [11, Annex A.2.1, Table A.2.1.1-2] The carrier frequency is 2 GHz and the BS transmit power is 43 dBm. An average vehicle penetration loss of 10 dB is assumed. The RSRP report is sent per 10-ms radio frame. The pools of HO parameters are $\mathcal{M} = \{-5, -4.5, \ldots, 11.5, 12\}$ in [dB], $\mathcal{T} = \{40, 64, 80, 100, 128, 160, 256, 320, 480, 512, 640, 1024, 2560\}$ in [ms]. The SINR threshold is defined as $\gamma^{th} = -6.5$ dB. If the channel outage holds for more than 200 ms, it is counted as a RLF. The ping-pong critical time is $T_{CRIT} = 5$ s.

Given the above simulation scenario, we first investigate the HO performance for a single user. Specifically, let a user move with speed of 120 km/h and cross the border between two cells (n, m) with the same trajectory for $10,000$ times. The probability mass function of t_{HO} is shown in Fig. 2(a) and compared against the analytical expression derived in Section III-B, for two values of TTT ($T = 64$ ms and $T = 100$ ms) and fixed value of HOM $M = 3$ dB. Note that the function is discrete, although with very high resolution (one slot = 10 ms). Then, closed-form and simulated outage probabilities (O_n^t, O_m^t) are shown in Fig. 2(b). The figure provides numerical validation of the results in Section III-A, as well as to Proposition 1, because of the monotonicity of both curves. Comparing Fig. 2(a) and Fig. 2(b), we observe that in this case choosing $T = 100$ ms is an incorrect setting as it would lead with high probability to “too-late” HO decisions. Fig. 3 shows that the proposed global objective function $F(M, T)$ with $\alpha_m = \alpha_n = 0.5$ is consistent with a HO metric defined as a weighted sum of L_RLFR, E_RLFR, and PPHR (with weight vector $(0.5, 0.25, 0.25)^T$). Thus, minimizing $F(M, T)$ provides a good trade-off between too-early and too-late HO metrics.

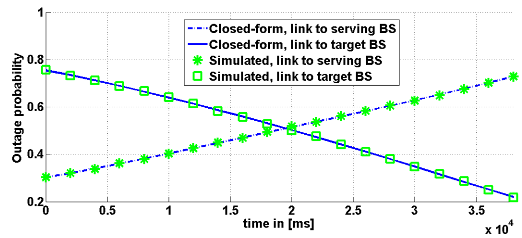
We then consider the impact of users’ mobility on the HO performance. To this purpose, we divide the users based on their mobility class and we compute the average user performance for each class in terms of two metrics: overall RLFR (L_RLFR + E_RLFR) and PPHR (implying unnecessary HOs). We compare three different strategies: 1) D-CDP: direct communication, default HO parameters $M = 3$ dB, $T = 100$ ms; 2) RCDP: relay aided communication, same default HO parameters as DCDP, 3) RCSDP: relay aided communication, scaled default parameters depending on the mobility classes [8], where the scaling factors are $(1, 0.5, 0.3)$ for mobility groups *middle* ($v \in [30, 80]$ km/h), *high* ($v \in (80, 160]$ km/h) and *ultra high* ($v \in (160, 300]$ km/h) respectively; 4) RCAP: proposed relay-aided adaptive HO parameter optimization algorithm. The results show that the relay aided communication improves the channel quality and reduces the HO-related RLFs. Among the three strategies for HO parameter configuration, our approach provides the best performance in terms of RLFs while keeping the PPHR at a reasonably low level, for the whole range of user velocities. In contrast, the DCDP and RCDP methods incurs a large number of RLFs, while RCSDP is sensitive to different velocities (mainly due to the heuristic choice of the scaling factors).

VI. Conclusion and Further Discussions

We presented a vehicle-specific HO optimization approach for vehicular users. The HO process aided by vehicle-mounted relays improves the communication links, and enables users

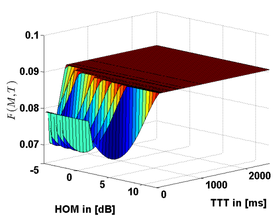


(a) Probability mass function of t_{HO}.

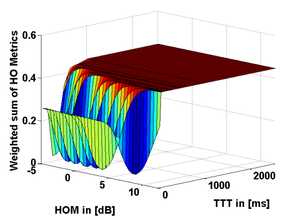


(b) Outage probabilities along user's trajectory.

Fig. 2. Comparison of closed-form expressions and simulated statistics for one user moving at 120km/h.

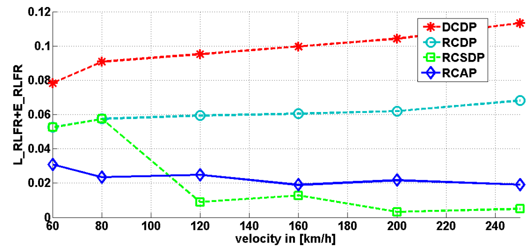


(a) Objective function $F(M,T)$.

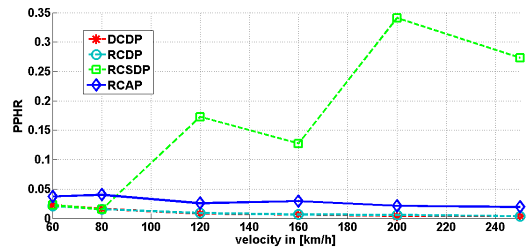


(b) Weighted sum of HO metrics

Fig. 3. Objective function vs. desired HO metrics.



(a) HO-related RLFR.



(b) PPHR

Fig. 4. Average performance vs. mobility class for different MRO strategies.

to obtain more context information. By utilizing the context information, we derived closed-form expressions of outage probabilities related to too-early and too-late HO events, and then formulate our objective function from the derived expressions. It is shown that the objective function reflects the properties of the desired HO metrics, and the analytical solution provides not only a good trade-off between minimization of HO-related RLFs and reduction of unnecessary HOs, but also a robust performance for different mobility states. To reduce the cost for user-specific computation and overheads, a possible extension of this work is to group the users according to the predicted context information (e.g., users with same route), and to optimize the user group-specific HO parameters using the same approach.

APPENDIX

We consider $i = n$ first. In the following we prove that $O_n^{t_{\text{HO}}} = \max_{t\in[t_0+1,t_{\text{HO}}]} O_n^t$, by showing that O_n^t in (7) is monotone increasing over $t \in [t_0+1, t_{\text{HO}}]$, because it is composed of two monotone increasing terms $-\exp\left(-\omega_i^t\gamma^{th}\beta_i^t\sigma^2\right)$ and $-(1+\omega_n^t\gamma^{th}\beta_n^t/\beta_m^t)^{-1}$, and a monotone nondecreasing term $-\prod_{j\neq n,m}(1+\omega_n^t\gamma^{th}\beta_n^t/\beta_j^t)^{-1}$. Firstly, if $E[R_n^t]$ is monotone decreasing, $\beta_n^t = 1/E[R_n^t]$ is monotone increasing. Due to the QoS requirement $\omega\log(1+R_n/\omega\sigma^2) \geq r^{th}$ and the monotonicity of $\omega_n\log(1+R_n/\omega_n\sigma^2)$ as a function of ω_n, ω_n is monotone increasing if R_n/σ^2 is positive and monotone decreasing. Secondly, if $E[R_m^t]$ is monotone increasing, β_n^t/β_m^t is also monotone increasing. Finally, we analyze β_n^t/β_j^t for $j \neq n, m$. Because the user moves either away from a BS or towards a BS during a short time period, $E[R_{j|j\neq n,m}^t]$ is either monotone increasing or monotone decreasing. If $E[R_{j|j\neq n,m}^t]$ is monotone increasing, then β_n^t/β_j^t is also monotone increasing. If $E[R_{j|j\neq n,m}^t]$ is monotone decreasing, then $E[R_{j|j\neq n,m}^t] \ll E[R_n^t]$ for $t \geq t_0$ under the assumption that the RSRP at time t_0 received from the neighboring BSs (except for the best candidate BS m) is far less than the RSRP from the serving BS, and we have $\beta_n^t/\beta_j^t \to 0$ and $(1+\omega_n^t\gamma^{th}\beta_n^t/\beta_j^t)^{-1} \to 1$ for $j \neq n, m$. Similarly we derive $O_m^{t_{\text{HO}}} = \max_{t\in[t_{\text{HO}},t_0+L]} O_m^t$ by proving that O_m^t is monotone decreasing over $t \in [t_{\text{HO}}, t_0+L]$.

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