

A Novel Handover Scheme for Hybrid LiFi and WiFi Networks

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Abstract—Combining the high transmission speed of light fidelity (LiFi) and the ubiquitous coverage of wireless fidelity (WiFi), hybrid LiFi and WiFi network (HLWNet) has attracted intensive research interest. While such a network can boost the system capacity, it faces a challenging issue in handover since the coverage areas of LiFi and WiFi completely overlap each other. Also, LiFi has a relatively short coverage range from a single access point (AP). As a result, HLWNets are susceptible to frequent handovers, in terms of both handovers between LiFi and WiFi and handovers between two LiFi APs. Therefore handover skipping was introduced, which enables handovers between two non-adjacent APs. Conventional handover skipping schemes rely on knowledge about the user's trajectory, and are difficult to implement in practice. Alternatively, the rate of change in reference signal received power (RSRP) can be used to reflect the user's moving direction. Based on this, an adaptive handover scheme is proposed in this paper, which varies the user's network preference according to the user's speed. Results show that in comparison with the standard and trajectory-based schemes, the proposed approach can improve user throughput by up to about 120% and 30%, respectively.

Index Terms—Light fidelity (LiFi), wireless fidelity (WiFi), hybrid network, handover skipping, reference signal received power (RSRP)

I. INTRODUCTION

GLOBAL mobile data traffic is expected to reach 48.3 exabytes per month at the end of 2021, growing over 4 times in 4 years [1]. The exponentially increasing demand for mobile data is bottlenecked by the scarce spectrum resource of radio-frequency (RF) [2]. This drives technologies that exploit higher frequencies, and among these technologies is visible light communication (VLC) and its network variation light fidelity (LiFi) [3]. With LiFi, the light intensity is modulated to carry information bits, and photodiodes (PDs) are used to detect the modulated optical signals. LiFi offers many advantages over wireless fidelity (WiFi), such as a much wider and unregulated spectrum and the ability to be used in RF-restricted areas. Recent research shows that with four colour off-the-shelf light-emitting diodes (LEDs), LiFi can provide a link data rate of above 15 Gbps [4].

To combine the high transmission speed of LiFi and the ubiquitous coverage of WiFi, hybrid LiFi and WiFi networks (HLWNets) are conceived [5]. Achieving a greater throughput than a stand-alone LiFi or WiFi network, HLWNets have drawn great attentions in research. Meanwhile, the handover

issue becomes more challenging since the coverage range of a single access point (AP) in such a network is relatively short, especially for LiFi. Apart from that, the coverage areas are completely overlapped between LiFi and WiFi. This will cause frequent handovers if signal strength strategy (SSS) is used, i.e. the user is assigned to the AP providing the highest reference signal received power (RSRP). Based on RSRP, the standard handover algorithm in the long-term evolution (LTE) model [6] adopts hysteresis to reduce the ping-pong effect. However this algorithm can only reduce the handover rate caused by the small coverage areas of APs by a limited amount.

The concept of handover skipping was proposed to avoid frequent handovers in ultra-dense networks [7]–[9]. In [7], a topology-aware skipping scheme based on the chord length of the cell was proposed. This method relies on the user's trajectory to obtain the length of the movement path within the coverage area of a certain AP. A similar method was reported in [8], with the scope of application being extended to multi-AP association. A velocity-aware handover approach was developed for heterogeneous networks in [9]. However, the above methods all need knowledge about the user's trajectory. As a result, they have two limitations: i) the measurement of the user's trajectory is less accurate in an indoor scenario because multiple reflections on surfaces cause errors; and ii) uplink transmission is required to send the trajectory information to the APs.

Instead of the user's trajectory, the change of rate in RSRP can be used to indicate whether the user is moving towards the central area of a certain AP [10]. Combining the value of RSRP and its rate of change can determine whether a neighbouring AP should be skipped in a homogeneous network. However, in a HLWNet the coverage areas of LiFi and WiFi overlap each other. The method in [10] is not able to avoid frequent handovers between LiFi and WiFi. In this paper, an adaptive handover scheme is proposed for HLWNets by introducing a network preference coefficient. Specifically, slow-moving users can select the AP providing the highest channel quality, while fast-moving users are allowed to stay within WiFi. Results show that the proposed method can improve the user throughput by up to 122% and 29% over the standard and trajectory-based handover methods, respectively.

The remainder of this paper is organised as follows. The system model is given in Section II, including the models of

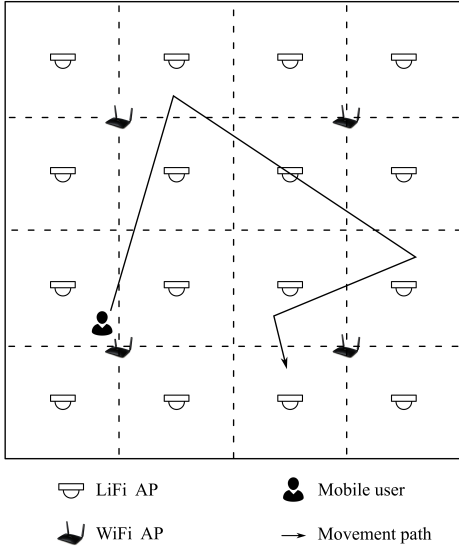


Fig. 1. Schematic of an indoor HLWNet.

network deployment, channel and light-path blockages. The standard handover scheme is introduced in Section III, and the novel method is proposed in Section IV. Simulation results are presented in Section VI. Finally, conclusions are drawn in Section VII.

II. SYSTEM MODEL

We consider an indoor HLWNet that consists of a number of WiFi and LiFi APs, as shown in Fig. 1. The entire room is sectionalized and one WiFi AP is placed in the centre of each section. The LiFi APs are arranged in a lattice topology, and each LiFi AP operates on a ceiling LED lamp. The WiFi system employs carrier sense multiple access/collision avoidance (CSMA/CA) to keep inter-cell interference (ICI) at an undetectable level. As for LiFi, adjacent 4 APs use different optical spectra to mitigate ICI. A random waypoint (RWP) approach [11] is adopted to model user movement in the room.

A. Channel Model

A LiFi channel has two parts: line-of-sight (LoS) and non line-of-sight (NLoS) paths. Let $d_{i,u}$ denote the Euclidean distance of the LoS path between AP i and user u . Let $\phi_{i,u}$ and $\psi_{i,u}$ denote the angles of irradiance and incidence, respectively. The LoS channel gain is given by [12, eq. (10)]:

$$H_{i,u}^{\text{LoS}} = \frac{(m+1)A_{\text{pd}}}{2\pi d_{i,u}^2} \cos^m(\phi_{i,u}) g_f g_c(\psi_{i,u}) \cos(\psi_{i,u}), \quad (1)$$

where $m = -\ln 2 / \ln(\cos \Phi_{1/2})$ is the Lambertian emission order, and $\Phi_{1/2}$ is the angle of half intensity; A_{pd} is the physical area of the photodiode (PD); g_f is the optical filter gain; $g_c(\psi_{i,u})$ denotes the optical concentrator gain, which is given by:

$$g_c(\psi_{i,u}) = \begin{cases} \frac{n^2}{\sin^2(\Psi_{\max})}, & 0 \leq \psi_{i,u} \leq \Psi_{\max} \\ 0, & \psi_{i,u} > \Psi_{\max} \end{cases}, \quad (2)$$

where n represents the refractive index, and Ψ_{\max} is the semi-angle of the field of view (FoV) of the PD.

As for NLoS paths, only first-order reflections are considered since higher-order reflections typically contribute little [12]. The NLoS channel gain is denoted by $H_{i,u}^{\text{NLoS}}$, and its expression is given by [13, eq. (3)]. The total gain of the LiFi channel is $H_{i,u} = H_{i,u}^{\text{LoS}} + H_{i,u}^{\text{NLoS}}$. At the receiver, the PD converts the captured photons into a photocurrent:

$$I = R_{\text{pd}} H_{i,u} P_{\text{mod}}, \quad (3)$$

where R_{pd} is the detector responsivity and P_{mod} denotes the average modulated optical power. The signal-to-interference-plus-noise ratio (SINR) of the LiFi link between AP i and user u is written as follows:

$$\gamma_{\text{LiFi}}^{i,u} = \frac{(R_{\text{pd}} H_{i,u} P_{\text{mod}})^2}{N_{\text{LiFi}} B_{\text{LiFi}} + \sum_{j \in \mathcal{I}, j \neq i} (R_{\text{pd}} H_{j,u} P_{\text{mod}})^2}, \quad (4)$$

where B_{LiFi} is the bandwidth of the LiFi AP; N_{LiFi} denotes the power spectral density (PSD) of noise, which is assumed to be signal independent; and \mathcal{I} is the set of APs that employ the same optical spectrum as AP i .

The SINR of the WiFi channel is denoted by $\gamma_{\text{WiFi}}^{i,u}$, which is expressed as:

$$\gamma_{\text{WiFi}}^{i,u} = \frac{G_{\text{WiFi}}^{i,u} P_{\text{WiFi}}}{N_{\text{WiFi}} B_{\text{WiFi}}}, \quad (5)$$

where B_{WiFi} and P_{WiFi} are the bandwidth and transmit power of the WiFi AP, respectively; N_{WiFi} denotes the PSD of noise at the receiver; and $G_{\text{WiFi}}^{i,u}$ is the WiFi channel gain, which is given by [13, eq. (8)].

B. Light-path Blockage

Regarding light-path blockages, two parameters are considered: occurrence rate and occupation rate [14]. The occurrence rate is the average number of blockages that occur in a time unit. The Poisson point process (PPP) is commonly used in queueing theory [15] to model random events such as the arrival of packages at a switch. We assume that the blockage events also follow a PPP. The occupation rate is the proportion of time that is occupied by blockages, and is assumed to be uniformly distributed between 0 and 1. Also, the blockages with respect to different APs are assumed to be independent.

C. Throughput

The WiFi capacity can be measured by Shannon capacity, which does not apply to LiFi as $\gamma_{\text{LiFi}}^{i,u}$ is an electrical SINR for non-negative signals. It is difficult to compute the equivalent SINR of quadratic signals from $\gamma_{\text{LiFi}}^{i,u}$, since this depends on the specific modulation scheme used. In [16], a lower bound of the LiFi channel was derived. This bound can be used for $\gamma_{\text{LiFi}}^{i,u}$. The capacity of the link between AP i and user u is then expressed as:

$$r_{i,u} = \begin{cases} \frac{B_i}{2} \log_2 \left(1 + \frac{e}{2\pi} \gamma_{\text{LiFi}}^{i,u} \right), & \text{for a LiFi AP} \\ B_i \log_2 \left(1 + \gamma_{\text{WiFi}}^{i,u} \right), & \text{for a WiFi AP} \end{cases}. \quad (6)$$

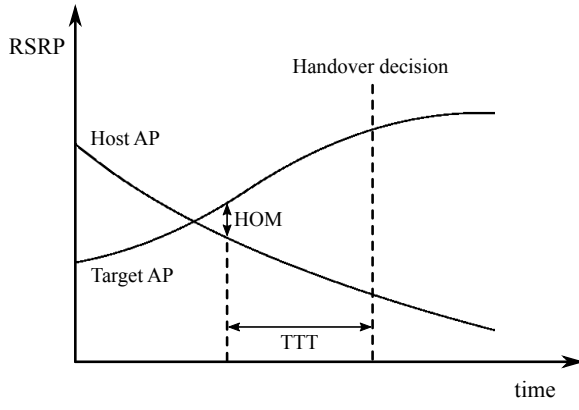


Fig. 2. The handover scheme in LTE.

III. STANDARD HANDOVER SCHEME

The handover scheme in LTE [6] employs hysteresis to mitigate the ping-pong effect. Fig. 2 shows the principle of this standard handover scheme, which is referred to as STD. Let P_{i_H} and P_{i_T} denote the values of RSRP for the host and target APs, respectively. Let δ_{HOM} and t_{TTT} denote the values of handover margin (HOM) and time to trigger (TTT), respectively. The STD scheme sets a time counter, which starts working when the following condition is met:

$$P_{i_T} > P_{i_H} + \delta_{\text{HOM}}. \quad (7)$$

The time counter continues as long as (7) is satisfied, and otherwise is reset. When the counted time reaches t_{TTT} , a handover decision is made to transfer the user from the host AP to the target one. The STD scheme has a minimum connection time of t_{TTT} , with a typical value of hundreds of milliseconds [6]. For a certain AP, the traverse time is defined as the period from the time point where P_i becomes the largest to the time point where P_i is no longer the largest. If the traverse time of an AP is shorter than TTT, then the STD scheme will skip this AP. Though the ability of handover skipping can be strengthened by increasing t_{TTT} , this will degrade the SINR performance due to the impact of hysteresis.

IV. PROPOSED HANDOVER SCHEME

Let ΔP_i denote the change in RSRP in a time unit. A large ΔP_i means the user is moving towards the central area of an AP, and a small ΔP_i means the user is moving along the edge area of an AP. For a homogeneous network, choosing the AP with the largest value of $P_i + \Delta P_i$ can consider both the signal strength and traverse time.

The situation is different in a HLWNet since the coverage areas of LiFi and WiFi overlap each other. Also, there are two handover types in a hybrid network: horizontal handover (HHO) and vertical handover (VHO). A HHO occurs between two APs in the same network, while a VHO happens between different networks. A VHO usually requires a much longer delay than a HHO [17], due to the change of the air interface. It is intuitive that fast-moving users should always be served by WiFi to avoid frequent handovers, including HHOs in LiFi

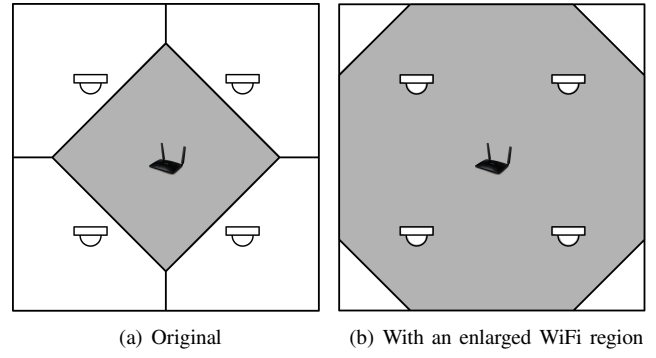


Fig. 3. The cellular topology of a HLWNet.

and VHOs between LiFi and WiFi. Fig. 3(a) presents the cellular topology of a HLWNet, where the border between two APs indicates that these APs have the same levels of SINR. In order to reduce the handover rate of fast-moving users, the WiFi coverage region needs to be enlarged, as shown in Fig. 3(b). To achieve this, the value of $P_i + \Delta P_i$ in WiFi is multiplied by a weight coefficient λ . Also, γ_i is used instead of P_i to accommodate the different noise levels between LiFi and WiFi. As a result, the objective function of the target AP in a HLWNet is written as:

$$\Gamma_i = \begin{cases} \gamma_i^{(t_0)} + \Delta\gamma_i, & \text{for LiFi} \\ \lambda (\gamma_i^{(t_0)} + \Delta\gamma_i), & \text{for WiFi} \end{cases}, \quad (8)$$

where $\Delta\gamma_i$ is the SINR difference between the starting and ending points of the time counter:

$$\Delta\gamma_i = \frac{\gamma_i^{(t_0+t_{\text{TTT}})} - \gamma_i^{(t_0)}}{t_{\text{TTT}}}. \quad (9)$$

The coefficient λ is dependant on the user's speed. For a static user, λ should be 1 to grant the user access to the AP providing the highest SINR. When the user moves fast, λ should be relatively large to enlarge the WiFi coverage region. The choice of λ will be studied in Section V.

The proposed handover method counts time in a way similar to STD. When the time counter achieves t_{TTT} , the AP providing the largest Γ_i is selected to be the target AP. It is worth noting that the target AP is not necessarily the one that triggers the time counter. A handover will not be immediately executed until the target AP meets the condition in (7). If the user changes its speed or direction before the handover is executed, the objective function in (8) will be recalculated to choose a new target AP. Let γ_{i_H} denote the SINR value of the host AP. Let t_c denote the output of the time counter. Let i_T and \mathcal{I} denote the target AP and the set of all APs, respectively. The pseudo code of the proposed handover method is given in Algorithm 1.

V. SIMULATION RESULTS

Monte Carlo simulations are implemented to evaluate the performance of the proposed method, with a comparison to STD and the trajectory-based handover skipping in [7]. All

Algorithm 1 Proposed Handover Skipping Scheme**Input:** $\gamma_{i_H}^{(t)}, \gamma_i^{(t)}, \forall i \in \mathcal{I}$ **Output:** i_T $t_c \leftarrow 0$ **while** $t_c < t_{TTT}$ **do** **if** $\gamma_i^{(t)} \leq \gamma_H^{(t)} + \delta_{HOM}, \forall i \in \mathcal{I}$ **then**
 $t_c \leftarrow 0$ **else if** $t_c = 0$ **then** $t_0 \leftarrow t$ **else** $t_c \leftarrow t - t_0$ **end if** $t \leftarrow t + 1$ **end while****if** i is a LiFi AP **then** $\Gamma_i \leftarrow \gamma_i^{(t_0)} + (\gamma_i^{(t_0+t_{TTT})} - \gamma_i^{(t_0)}) / t_{TTT}$ **else if** i is a WiFi AP **then** $\Gamma_i \leftarrow \lambda [\gamma_i^{(t_0)} + (\gamma_i^{(t_0+t_{TTT})} - \gamma_i^{(t_0)}) / t_{TTT}]$ **end if** $i_T \leftarrow \max\{\Gamma_i\}$ TABLE I
SIMULATION PARAMETERS

Parameter	Value
Room size (length by width by height)	10 × 10 × 3 m
The physical area of the PD, A_{pd}	1 cm ²
Optical filter gain, g_f	1
Refractive index, n	1.5
Half-intensity radiation angle, $\Phi_{1/2}$	60°
FoV semi-angle of the PD, Ψ_{max}	90°
Detector responsivity, R_{pd}	0.53 A/W
Wall reflectivity	0.8
Modulated optical power per LiFi AP, P_{mod}	1 Watt
Transmitted power per WiFi AP, P_{WiFi}	20 dBm
Bandwidth per LiFi AP, B_{LiFi}	20 MHz
Bandwidth per WiFi AP, B_{WiFi}	20 MHz
PSD of noise in LiFi, N_{LiFi}	10 ⁻²¹ A ² /Hz [5]
PSD of noise in WiFi, N_{WiFi}	-174 dBm/Hz [5]

methods use the same HOM and TTT, which are set to be 1 dB and 160 ms [6], to provide a fair comparison. A HLWNet containing 4 WiFi APs and 16 LiFi APs is considered. The nearest LiFi APs are separated at a distance of 2.5 m. The height between the user and the LiFi APs is 3 m. The average overhead of HHO is about 200 ms in wireless local area networks (WLANs), while the average overhead of VHO is set to be 500 ms [13]. Other parameters are summarised in Table I.

A. Choice of the Weight Coefficient

Fig. 4 shows the user throughput achieved by the proposed method as a function of the weight coefficient λ . As λ increases, the throughput increases first and then decreases for $v = 0.1$ m/s and 1.5 m/s. This is because a slow-moving user needs an adequate λ to switch between LiFi and WiFi. As for

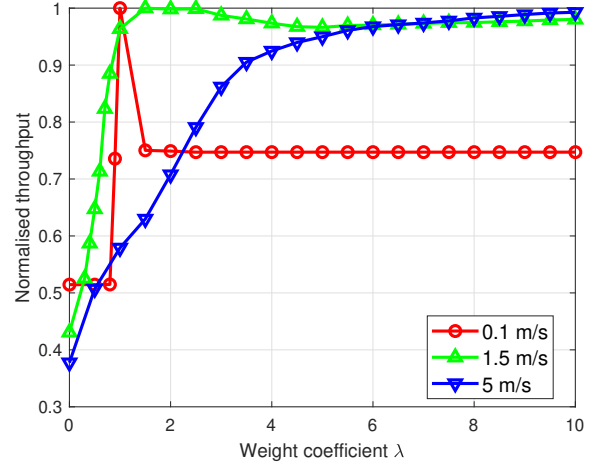
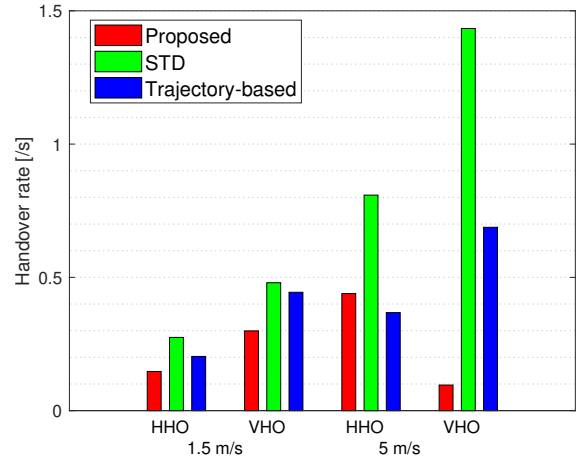
Fig. 4. User throughput versus the weight coefficient λ .

Fig. 5. Handover rates of HHO and VHO.

$v = 5$ m/s, the throughput increases towards a saturation, since it is better to restrict a fast-moving user to WiFi. In general, the optimal λ increases as the user's speed.

B. Handover Rate

The handover rates of HHO and VHO are presented in Fig. 5. As can be seen, the proposed method achieves a lower handover rate than the others, especially when the user is moving fast. At $v = 5$ m/s, the proposed method can significantly suppress the VHO rate, leading to a decrease of 93% and 85% in comparison with STD and the trajectory-based method, respectively. Against these methods, the proposed method can reduce the overall handover cost by 84% and 67%.

C. Throughput

Fig. 6 presents the user throughput as a function of the user's speed. As shown, all methods obtain almost the same throughput when v is below 1.5 m/s. This is because the optimal λ for the proposed method is 1 in this case. In other

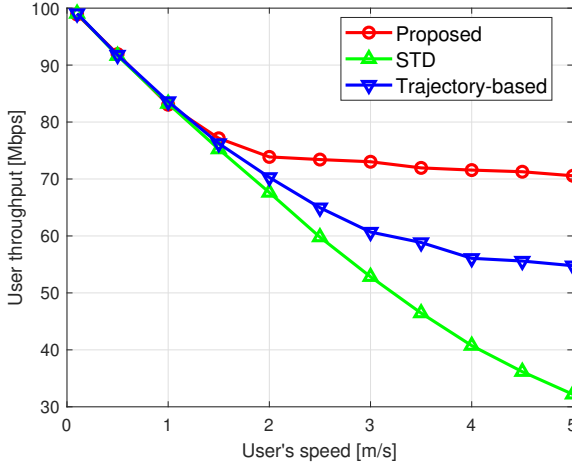


Fig. 6. User throughput versus the user's speed.

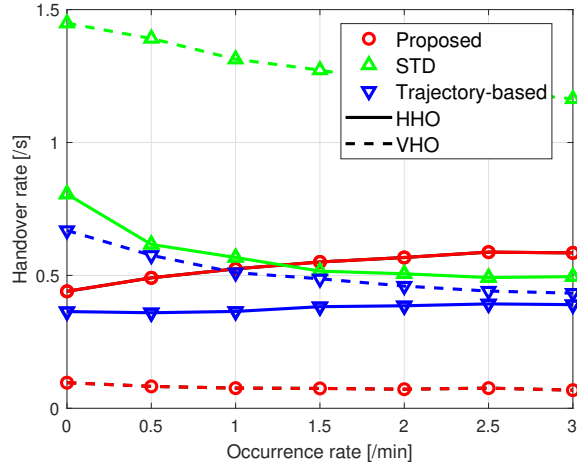


Fig. 7. Handover rate versus the occurrence rate of light-path blockages.

words, the user chooses the AP that provides the highest SINR, in the same way as STD. As the user's speed increases, the throughput gaps between the proposed scheme and the other methods become significant. At $v = 5$ m/s, for example, the proposed method obtains a user throughput of 71 Mbps, 122% and 29% higher than STD and the trajectory-based method, respectively.

D. Impact of Light-path Blockages

Finally, the effects of light-path blockages are studied in Fig. 7, with $v = 5$ m/s being taken as an example. For STD, the rates of HHO and VHO both noticeably decrease as the occurrence rate increases. This is because the user has to be served by WiFi during light-path blockages. Consequently, the HHO rate in LiFi reduces, as well as the VHO rate between LiFi and WiFi. In contrast, the proposed method has an increase in the HHO rate, with a barely changed VHO rate. Nevertheless, the overall handover rate of the proposed method is still much lower than that of STD.

VI. CONCLUSIONS

A novel handover scheme was proposed for HLWNets in this paper. This scheme combines RSRP and its rate of change to decide whether an AP should be skipped. Also, the proposed scheme provides an adaptive WiFi coverage according to the user's speed. This allows a fast-moving user to stay in WiFi to avoid frequent handovers. On the contrary, a slow-moving user prefers to choose the AP that offers the highest SINR. Results show that compared to STD, the proposed scheme can reduce the handover rate by 41% at 1.5 m/s and 76% at 5 m/s. The proposed scheme can also increase throughput by up to 122% and 29% over STD and trajectory-based handover skipping, respectively.

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