

RESEARCH ARTICLE

New Vertical Handover Method to Optimize Utilization of Wireless Local Area Network in High-Speed Environment

Hoe Tung Yew¹, Eko Supriyanto², Muhammad Haikal Satria^{3*}, Yuan Wen Hau⁴

1 Faculty of Engineering, Universiti Malaysia Sabah, Kota kinabalu, Malaysia, **2** IJN-UTM Cardiovascular Engineering Centre, Faculty of Biosciences and Medical Engineering, Universiti Teknologi Malaysia, Skudai, Malaysia, **3** Faculty of Biosciences and Medical Engineering, Universiti Teknologi Malaysia, Skudai, Malaysia, **4** IJN-UTM Cardiovascular Engineering Centre, Faculty of Biosciences and Medical Engineering, Universiti Teknologi Malaysia, Skudai, Malaysia

* mhaikal@utm.my



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Citation: Yew HT, Supriyanto E, Satria MH, Hau YW (2016) New Vertical Handover Method to Optimize Utilization of Wireless Local Area Network in High-Speed Environment. PLoS ONE 11(11): e0165888. doi:10.1371/journal.pone.0165888

Editor: Kim-Kwang Raymond Choo, University of Texas at San Antonio, UNITED STATES

Received: February 13, 2016

Accepted: September 14, 2016

Published: November 4, 2016

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Data Availability Statement: All the data, figures and tables are available at figshare, <https://figshare.com/s/3fdbf08238025549ec9a>.

Funding: This research is supported by the Ministry of Education Malaysia and Universiti Teknologi Malaysia under Grant No. Q. J130000.2745.02K17, R.J130000.7309.4B120, R. J130000.7309.4B121, R.J130000.7309.4B122, and R.J130000.7309.4B123. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Abstract

In heterogeneous wireless networks, wireless local area network (WLAN) is highly preferred by mobile terminals (MTs) owing to its high transmission bandwidth and low access cost. However, in high-speed environment, handover from a cellular network to a WLAN cell will lead to a high number of handover failures and unnecessary handovers due to the WLAN coverage limitation and will become worse at high speed. A new vertical handover method is proposed to minimize the probability of handover failure and unnecessary handover while maximizing the usage of WLAN in high-speed environment. The simulation results show that the proposed method kept the probability of handover failure and unnecessary handover below 0.5% and 1%, respectively. Compared with previous studies, the proposed method reduced the number of handover failures and unnecessary handovers up to 80.0% and 97.7%, respectively, while the MT is highly mobile. Using the proposed prediction method, the MT can benefit high bandwidth and low network access cost from the WLAN with minimum interruption regardless of speed.

Introduction

Next-generation wireless networks will be driven by an all-IP-based network infrastructure that provides seamless mobility and ubiquitous access to Internet through heterogeneous wireless networks [1]. In heterogeneous wireless network, wireless local area network (WLAN) is highly preferred owing to its high capacity and low access cost [2, 3]. However, because of limited WLAN coverage, handover from a cellular network to the WLAN may lead to a high number of handover failures and unnecessary handovers when a mobile terminal (MT) is in a high-speed environment because the MT requires less time to cross the WLAN coverage when the speed increases [3, 4].

Handover failure occurs when the MT traveling time within a WLAN (T_{WLAN}) is less than the handover latency from a cellular network to the WLAN (T_i). The MT leaves the WLAN

Competing Interests: The authors have declared that no competing interests exist.

coverage before the handover process is executed causing network connection breakdown and service interruption [3–5]. On the other hand, if T_{WLAN} is equal to or less than the total time of handover to (T_i) and out of (T_o) the WLAN coverage ($T_{WLAN} \leq (T_i + T_o)$), unnecessary handover occurs [6]. In this situation, the MT does not transmit or receive any data packet via the WLAN because the MT triggers handover out of the WLAN only after completion of handover into the WLAN. Unnecessary handover is undesirable because it wastes network resources [7].

At present, WLAN application is restricted to static or pedestrian navigation environment [8]. For example, in the patient monitoring system using heterogeneous wireless networks proposed by Niyato et al. [2], WLAN was used only for communication within a building such as mall, clinic, hospital, and home. Furthermore, most of the existing handover decision-making algorithms predefined a speed threshold for the WLAN where the MT handovers to the WLAN if and only if the speed of MT is lower than the threshold to prevent unnecessary handover to the WLAN at high mobility. The network-selection algorithms presented in [9–12] defined the WLAN speed threshold at 5 m/s and below. In addition, the fuzzy multi-criteria-based vertical handover algorithm presented by Kaleem et al. [13] and Yew et al. [14] set the rule: “if MT velocity (v) is low, then the probability of WLAN rejection is low; else the probability of WLAN rejection is high.”

Yan et al. [6] and Hussain et al. [15] presented a traveling distance prediction-based vertical handover scheme to minimize the number of handover failures and unnecessary handovers to WLAN with assumption that MT travels in constant speed within the WLAN coverage. In these schemes, MTs have to take two received signal strength (RSS) sample points within a WLAN cell. The first RSS sample point is at the point where the MT detects a predefined RSS threshold (P_{In_RSSth}), and the second sample point (s , as shown in Fig 1) can be any point within the WLAN cell (after the MT enters the WLAN cell). The trigonometric function is then applied to predict the MT traveling distance within the WLAN cell. The MT triggers handover to the WLAN if and only if the estimated traveling distance within the WLAN is greater than the distance threshold (L_{th}). The L_{th} of handover failure presented by Yan et al. [6] (L_{thfY}) and Hussain et al. [15] (L_{thfH}) is expressed as

$$L_{thfY} = 2r \sin \left(\sin^{-1} \left(\frac{v(T_i)}{2r} \right) - \frac{\pi P_f}{2} \right) \quad (1)$$

$$L_{thfH} = \frac{2r \tan \left(\tan^{-1} \left(\frac{v(T_i)}{\sqrt{4r^2 - v^2 T_i^2}} \right) - \frac{\pi P_f}{2} \right)}{\sqrt{1 + \left(\tan \left(\tan^{-1} \left(\frac{v(T_i)}{\sqrt{4r^2 - v^2 T_i^2}} \right) - \frac{\pi P_f}{2} \right) \right)^2}} \quad (2)$$

The unnecessary handovers L_{th} presented by Yan et al. [6] (L_{thuY}) and Hussain et al. [15] (L_{thuH}) are expressed as

$$L_{thuY} = 2r \sin \left(\sin^{-1} \left(\frac{v(T_i + T_o)}{2r} \right) - \frac{\pi P_u}{2} \right) \quad (3)$$

$$L_{thuH} = \frac{2r \tan \left(\tan^{-1} \left(\frac{v(T_i + T_o)}{\sqrt{4r^2 - v^2 (T_i + T_o)^2}} \right) - \frac{\pi P_f}{2} \right)}{\sqrt{1 + \left(\tan \left(\tan^{-1} \left(\frac{v(T_i + T_o)}{\sqrt{4r^2 - v^2 (T_i + T_o)^2}} \right) - \frac{\pi P_f}{2} \right) \right)^2}} \quad (4)$$

where r is the WLAN radius, v is the measured MT's velocity, and P_u and P_f denote the user-

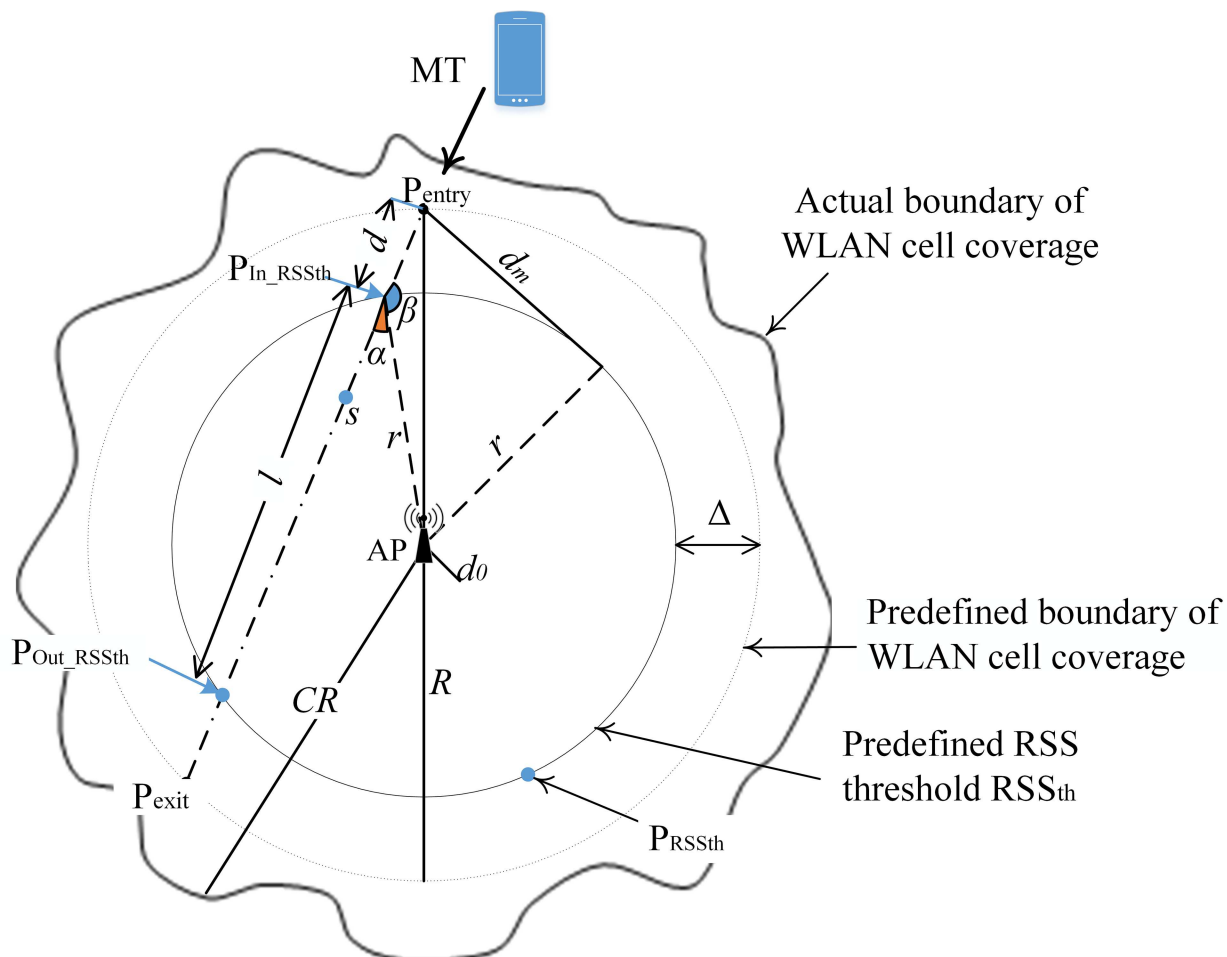


Fig 1. MT traveling trajectory in WLAN cell coverage.

doi:10.1371/journal.pone.0165888.g001

acceptable probability of unnecessary handover and handover failure, respectively. The results show that both the probability of handover failure and unnecessary handover are kept within the user acceptable value [6, 15]. However, the optimum time to take the second RSS sample point was not considered by the authors. We have found that the larger the time gap between the two RSS sample points is, the lower becomes the accuracy of the prediction result. The time needed by the MT to cover the two RSS sample points is expressed as $t_s - t_{P_{InRSSth}}$, where t_s is the time of the MT at the second RSS sample point s and $t_{P_{InRSSth}}$ is the time of the MT at the first sample point $P_{InRSSth}$ (Fig 1). Therefore, using the methods presented by Yan et al. [6] and Hussain et al. [15], the actual beneficial time (AT_{WLAN}) for the MT should be

$$AT_{WLAN} = T_{WLAN} - (t_s - t_{P_{InRSSth}}) \quad (5)$$

In this paper, a novel vertical handover method is proposed to improve the accuracy of the traveling-time estimation and to minimize both handover failure and unnecessary handover to the WLAN when the MT is in a high-speed environment.

Proposed Vertical Handover Method

Fig 1 shows the MT travel trajectory in WLAN cell coverage. We assume that the MT crosses the WLAN cell from an entry point (P_{entry}) to an exit point (P_{exit}) (as shown in Fig 1) at irregular speed (accelerate or decelerate). The beneficial time (T_{WLAN}) for the MT within the WLAN cell is defined as the time the MT travels from points $P_{\text{In_RSSth}}$ to $P_{\text{Out_RSSth}}$. The MT would only be able to benefit from the connected WLAN cell if $T_{\text{WLAN}} > (T_i + T_o)$.

In Fig 1, R denotes the distance between P_{exit} or P_{entry} and the WLAN access point (AP), P_{RSSth} is any point that falls on the predefined RSS_{th} line, r is the distance between P_{RSSth} and AP, and d is the MT traveling distance from P_{entry} to $P_{\text{In_RSSth}}$. d is expressed as

$$d = t_d * \frac{v_e + v_R}{2}, \quad d \in [\Delta, d_m] \quad (6)$$

where t_d is time taken by the MT to travel from P_{entry} to $P_{\text{In_RSSth}}$, v_e and v_R denotes velocity at P_{entry} and $P_{\text{In_RSSth}}$ respectively, which can be measured using an accelerometer or velocity estimation algorithm in [16], Δ is the minimum value of d , namely, $(R-r)$, and d_m represents the maximum d value, $(\sqrt{R^2 - r^2})$. The R and r values can be determined based on the RSS value measured at points P_{entry} ($\text{RSS}_{P_{\text{entry}}}$) and $P_{\text{In_RSSth}}$ ($\text{RSS}_{P_{\text{In_RSSth}}}$), respectively, using the log-distance path loss model [17], as expressed by (7).

$$\begin{aligned} \text{RSS}_{P_{\text{entry}}} &= P_{\text{TX}} - PL_0 - 10n \log \frac{R}{d_0} + \epsilon \\ 10n \log \frac{R}{d_0} &= P_{\text{TX}} - PL_0 - \text{RSS}_{P_{\text{entry}}} + \epsilon \\ \log \frac{R}{d_0} &= \frac{P_{\text{TX}} - PL_0 - \text{RSS}_{P_{\text{entry}}} + \epsilon}{10n} \\ R &= d_0 * 10^{\left(\frac{P_{\text{TX}} - PL_0 - \text{RSS}_{P_{\text{entry}}} + \epsilon}{10n} \right)} \end{aligned} \quad (7)$$

where d_0 is the distance between the AP and a reference point, P_{TX} is the AP transmit power, PL_0 is the power loss at the reference point, n is the path loss exponent, and ϵ is a zero-mean Gaussian random variable caused by shadow fading. A low-pass filter can be used to suppress the shadowing part [18]. Similarly, the r value can be calculated by replacing $\text{RSS}_{P_{\text{entry}}}$ in (7) with $\text{RSS}_{P_{\text{In_RSSth}}}$.

In this paper, we assume Doppler shift problem caused by high mobility can be mitigated by using the Doppler diversity. In [19], Doppler domain multiplexing communication structure is proposed to achieve the maximum Doppler diversity in time varying fading. Furthermore, the Doppler frequency offset estimation and compensation algorithms presented in [20, 21] can be used to alleviate the Doppler effects in high-speed environment.

The RSS value is monitored by MT periodically at time interval of T_m which is given by $\frac{D_s}{v}$ second, where v is the measured MT's velocity and D_s is a fixed sampling distance of 1 m [22]. N number of RSS samples is collected over the time interval of ρ and the median value is selected to determine the distance between MT and AP. This is to minimize the impact of RSS fluctuation. The median method [shown in (8)] is used instead of the mean method [23] because it overcomes a sudden large increase or decrease in the RSS value caused by an

unintended factor. Therefore, RSS value is given as

$$RSS = Med\{RSS_1, RSS_2, \dots, RSS_N\}. \quad (8)$$

The number of samples N is adjusted dynamically to the MT's traveling velocity expressed as

$$N = \left\lceil \frac{\rho}{T_s} \right\rceil \quad (9)$$

where T_s is RSS sampling time ($T_s = 1$ ms) and $\rho = K * T_m$, $K \in [0.1, 0.9]$. The maximum number of RSS samples is limited to 30 to avoid excessive sampling at low traveling speed. Once the d , R , and r values are obtained, angle β can be determined using the cosine law as follows:

$$\begin{aligned} R^2 &= d^2 + r^2 - 2dr \cos \beta \\ \beta &= \arccos \frac{d^2 + r^2 - R^2}{2dr} \end{aligned} \quad (10)$$

By knowing β , we can determine angle α by

$$\alpha = \pi - \beta, \quad \frac{\pi}{2} < \beta < \pi. \quad (11)$$

Then, we can calculate the traveling distance l .

$$\begin{aligned} r^2 &= r^2 + l^2 - 2rl \cos \alpha \\ l &= 2r \cos \alpha \end{aligned} \quad (12)$$

From (11)

$$\cos \alpha = \cos(\pi - \beta) = -\cos \beta \quad (13)$$

Substituting (13) into (12) yields

$$\begin{aligned} l &= -2r \cos \beta \\ \beta &= \arccos \left(-\frac{l}{2r} \right) \end{aligned} \quad (14)$$

Substituting (14) into (10) yields distance l as

$$\begin{aligned} \arccos \left(-\frac{l}{2R} \right) &= \arccos \frac{d^2 + r^2 - R^2}{2dr} \\ -\frac{l}{2r} &= \frac{d^2 + r^2 - R^2}{2dr} \\ l &= -\left(\frac{d^2 + r^2 - R^2}{d} \right) = \frac{R^2 - r^2 - d^2}{d} \end{aligned} \quad (15)$$

By applying the kinematic equation, l also can be expressed as

$$l = \frac{1}{2} c T_{WLAN}^2 + v_R T_{WLAN} \quad (16)$$

where c denotes MT's acceleration or deceleration rate. It can be determined by

$$c = \frac{v_R - v_e}{t_d} = \frac{v_R - v_e}{|t_R - t_e|} \quad (17)$$

where t_R and t_e represent the time of the MT passes through P_{In_RSSth} and P_{entry} , respectively.

Next, we derive d from (15).

$$\begin{aligned} ld &= R^2 - r^2 - d^2 \\ d^2 + ld + (r^2 - R^2) &= 0 \\ d &= \frac{-l + \sqrt{l^2 - 4(r^2 - R^2)}}{2}, \quad d > 0 \end{aligned} \quad (18)$$

Instead of using the time threshold similar to what were previously presented in [6, 15], we introduce a threshold for distance d known as d_{th} so that the MT can make handover decision by comparing the measured d value with d_{th} directly. We can derive d_{th} from (18) by replacing l with l_{th} and d with d_{th} . It is given as

$$d_{th} = \frac{-l_{th} + \sqrt{l_{th}^2 - 4(r^2 - R^2)}}{2}, \quad d_{th} > 0 \quad (19)$$

where l_{th} is the traveling distance threshold. From (16), l_{th} for handover failure l_{thf} and unnecessary handover l_{thu} can be expressed as

$$l_{thf} = \frac{1}{2}cT_i^2 + v_R T_i \quad (20)$$

$$l_{thu} = \frac{1}{2}c(T_i + T_o)^2 + v_R(T_i + T_o) \quad (21)$$

In constant speed ($c = 0$), $l_{thf} = v_R T_i$ and $l_{thu} = v_R(T_i + T_o)$ which are identical to Yan et al.'s method as shown in (1) and (3) if both P_f and P_u are equal to 0. By substituting (20) into (19) yields d_{thf} for handover failure d_{thf} as

$$d_{thf} = \frac{-\left(\frac{1}{2}cT_i^2 + v_R T_i\right) + \sqrt{\left(\frac{1}{2}cT_i^2 + v_R T_i\right)^2 - 4(r^2 - R^2)}}{2} \quad (22)$$

Similarly, d_{th} for unnecessary handover d_{thu} can be determined by substituting (21) into (19) and it is given as

$$d_{thu} = \frac{-\left(\frac{1}{2}c(T_i + T_o)^2 + v_R(T_i + T_o)\right) + \sqrt{\left(\frac{1}{2}c(T_i + T_o)^2 + v_R(T_i + T_o)\right)^2 - 4(r^2 - R^2)}}{2} \quad (23)$$

The relationship between d and l is shown in Fig 2A, which shows that d inversely varies with l , indicating that the greater the traveling distance within WLAN coverage l is, the smaller is the d value. Referring to (22) and (23), both d_{thu} and d_{thf} are depending on the handover latency, acceleration or deceleration rate and velocity. By setting the handover latency (T_i and T_o) at 1 second [6, 15], the correlation of d_{th} (d_{thu} and d_{thf}), c , and v_R is shown in Fig 2B, where the d_{th} value decreases when the MT's velocity increases or speeds up. The proposed method triggers a handover to the WLAN if and only if measured d value is less than estimated d_{th} value.

Performance Evaluation

The scenario as shown in Fig 1 was simulated using OPNET. The WLAN cell is expected within the coverage of cellular network. We assume that the MT was connected to cellular network and seek for the availability of a WLAN. MT initiates the prediction process when the measured WLAN's RSS value is greater than the predefined $RSS_{P_{entry}}$ (MT reached point P_{entry}). In the prediction process, MT calculates the d , d_{thf} and d_{thu} value based on the v_R , v_e , t_R , t_e , R and r values measured at point P_{entry} and P_{In_RSSth} (measured WLAN's RSS value $> RSS_{th}$). If calculated d value is less than the d_{th} value (d_{thf} and d_{thu}), MT triggers handover to WLAN cell. Otherwise, it remains connected to cellular network.

In this experiment, 10,000 random trajectories were generated for MT to cross the WLAN coverage at speeds from 11.11 to 41.66 m/s (40 to 150 km/h) in 2.22 m/s (8 km/h) increments. The simulation parameters listed in Table 1 were selected to observe the performance of the proposed method. The radius r is set as 50 m and the total handover latency for the handover into and out of the WLAN was 2 seconds as in [6, 15]. The traveling time within the WLAN coverage was nearly equal to the total handover latency when the MT velocity reached 150 km/h. As a result, unnecessary handover always occurred when the speed of the MT was higher than 150 km/h.

The experiment was simulated within two scenarios. First scenario is that the MT crosses the WLAN cell in random direction with speed remaining fixed ($c = 0$) within the WLAN coverage [6, 15]. The second scenario is that the MT crosses the WLAN coverage in random direction with smooth acceleration in the range of 1 m/s² to 5 m/s². The deceleration condition is not critical to handover failure and unnecessary handover because it offers MT longer traveling time within the WLAN coverage. Therefore, deceleration condition was not considered in this experiment.

In order to generate random trajectories within the WLAN coverage, a random AP coordinate was generated in this experiment. The x coordinate of the AP was fixed at 100, but the y coordinate ($random_y$) was a random value within the range of $-r$ to r ($r = 50$). This is to ensure that all the trajectories are crossing the WLAN coverage. The distance of each trajectory is 200 m. The actual traveling distance within the WLAN coverage (D) is expressed as [6]

$$D = 2\sqrt{r^2 - h^2} \quad (24)$$

where $h = |AP\ y\ coordinate - MT\ y\ coordinate|$, as shown in Fig 3. The MT x coordinate ($random_x$) was randomly set from 0 to 30 m ($random_x \in [0,30]$) to create a different starting point for each MT when it moves toward the WLAN coverage.

The handover failure and unnecessary handover occur if the actual traveling time within the WLAN coverage (T_{WLAN}) is less than T_i and $T_i + T_o$, respectively. The actual traveling time within the WLAN coverage for first scenario ($c = 0$) can be determined by $\frac{D}{v}$. In the second scenario ($c = 1 \sim 5\ m/s^2$), the actual traveling time within the WLAN coverage can be calculated by

$$\begin{aligned} D &= \frac{1}{2}cT_{WLAN}^2 + v_R T_{WLAN} \\ \frac{1}{2}cT_{WLAN}^2 + v_R T_{WLAN} - D &= 0 \\ T_{WLAN} &= \frac{-v_R + \sqrt{v_R^2 - 2cD}}{c}, \quad c > 0 \end{aligned} \quad (25)$$

The pseudo code of determine the number of handover failures and unnecessary handovers is shown in Fig 4.

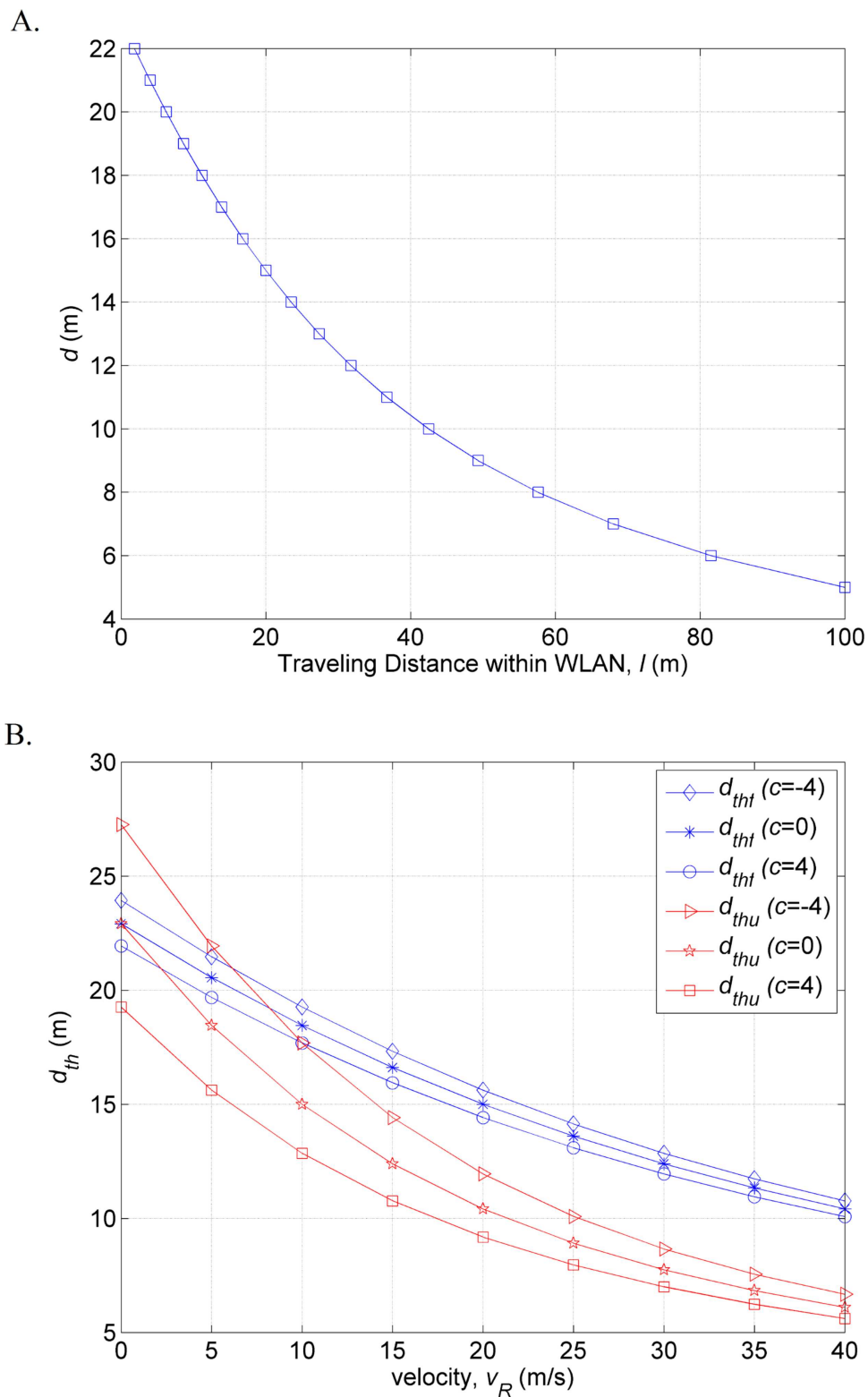


Fig 2. Relationship between (A) the d value and traveling distance l and (B) d_{th} , acceleration and velocity.

doi:10.1371/journal.pone.0165888.g002

Table 1. Simulation parameters.

Parameter	Value
AP physical characteristics	HT PHY 2.4GHz (802.11n)
RSS at P_{entry} , $RSS_{P_{\text{entry}}}$	-80.2 dBm
RSS threshold, RSS_{th}	-79.3 dBm
Number of Trajectory	10,000
Adaptive sensing time interval	$1/v$
R	55 m
r	50 m [6]
v	11.11 to 41.66 m/s
c (first scenario)	0
c (second scenario)	Random (1 ~ 5 m/s ²)
$t_s - t_{P_{\text{In_RSSth}}}$	0.1, 0.2 s
K	0.2
T_s	0.001 s
T_i	1 s [6, 15]
T_o	1 s [6, 15]
Time threshold for handover failure	T_f [6, 15]
Time threshold for unnecessary handover	$T_f + T_o$ [6, 15]
Tolerable handover failure probability, P_f	0
Tolerable unnecessary handover probability, P_u	0

doi:10.1371/journal.pone.0165888.t001

The performance of the proposed method is compared against the existing methods from Yan et al. [6] and Hussain et al. [15]. Fig 5 shows the total number of handovers performed by the existing methods and the proposed methods for the speeds from 11.11 to 41.66 m/s. Fig 5A shows that in the first scenario, all the methods have identical number of handovers based on the handover failure thresholds (d_{thf} , L_{thfY} , and L_{thfH} , respectively) defined by each method. In terms of the triggered handovers based on the unnecessary handover threshold (d_{thu} , L_{thuY} , and L_{thuH} , respectively), the method of Hussain et al. has higher number of handovers than the other methods (Fig 5B). In the second scenario, the number of handovers attained by the proposed method is lower than the first scenario. This is due to the smaller d_{th} value as the MT accelerates (shown in Fig 2B). However, the previous methods [6, 15] have same number of handovers as first scenario because these methods do not consider speed change and assumed all the MTs cross the WLAN coverage in constant speed.

The number of handover failures and unnecessary handovers were determined by applying different values of $t_s - t_{P_{\text{In_RSSth}}}$ (in Table 1) to the previous methods [6, 15]. The simulation results shown in Fig 6 show that the larger the value of $t_s - t_{P_{\text{In_RSSth}}}$ is, the higher is the number of handover failures and unnecessary handovers when the MT traveling speed increases. However, the proposed method is not affected by the $t_s - t_{P_{\text{In_RSSth}}}$ value because it completes the traveling distance prediction process when MT reaches $P_{\text{In_RSSth}}$. In contrast, the previous works initiated the prediction process after the MT reached $P_{\text{In_RSSth}}$.

In the second scenario ($c = \text{Random}$), the traveling time in WLAN coverage is always less than the time in the first scenario due to the acceleration. Therefore, the previous methods have even more handover failures and unnecessary handovers in the second scenario owing to the previous methods assuming MT remains at constant speed within WLAN coverage. Fig 6 shows the number of handover failures and unnecessary handovers obtained by the proposed method are much lower than the previous methods.

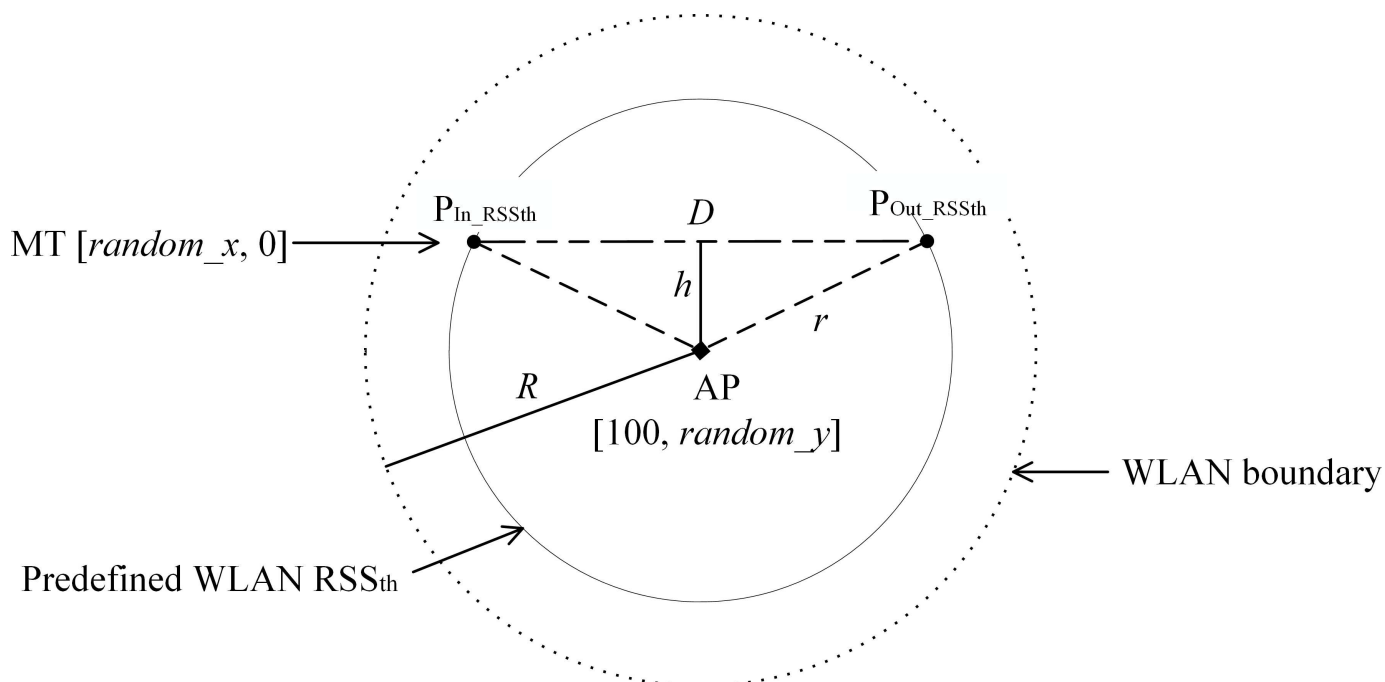


Fig 3. Scenario of MT traveling trajectory in the WLAN coverage.

doi:10.1371/journal.pone.0165888.g003

For better comparison of the performance results, we divided the number of handover failures and unnecessary handovers by the total number of handovers. Fig 7 shows that the ratio of handover failures and unnecessary handovers of the proposed methods are below 0.005 and 0.01 for both scenarios. It outperforms the previous methods that have been presented in [6, 15]. The handover failures and unnecessary handovers ratio of the proposed method rise while the MTs travel at higher speed. This is due to the fewer RSS samples collected by MT at higher

```

1:  IF Measured  $d$  value  $< d_{thf}$ 
2:    Number of handover based on  $d_{thf}$  = Number of handover based on  $d_{thf}$  + 1;
3:    IF  $T_{WLAN} < T_i$ 
4:      Number of handover failure = Number of handover failure + 1;
5:    END IF
6:  END IF
7:  IF Measured  $d$  value  $< d_{thu}$ 
8:    Number of handover based on  $d_{thu}$  = Number of handover based on  $d_{thu}$  + 1;
9:    IF  $T_{WLAN} < T_i + T_o$ 
10:     Number of unnecessary handover = Number of unnecessary handover + 1;
11:   END IF
12: END IF

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Fig 4. Pseudo code for determine number of handover failures and unnecessary handovers.

doi:10.1371/journal.pone.0165888.g004

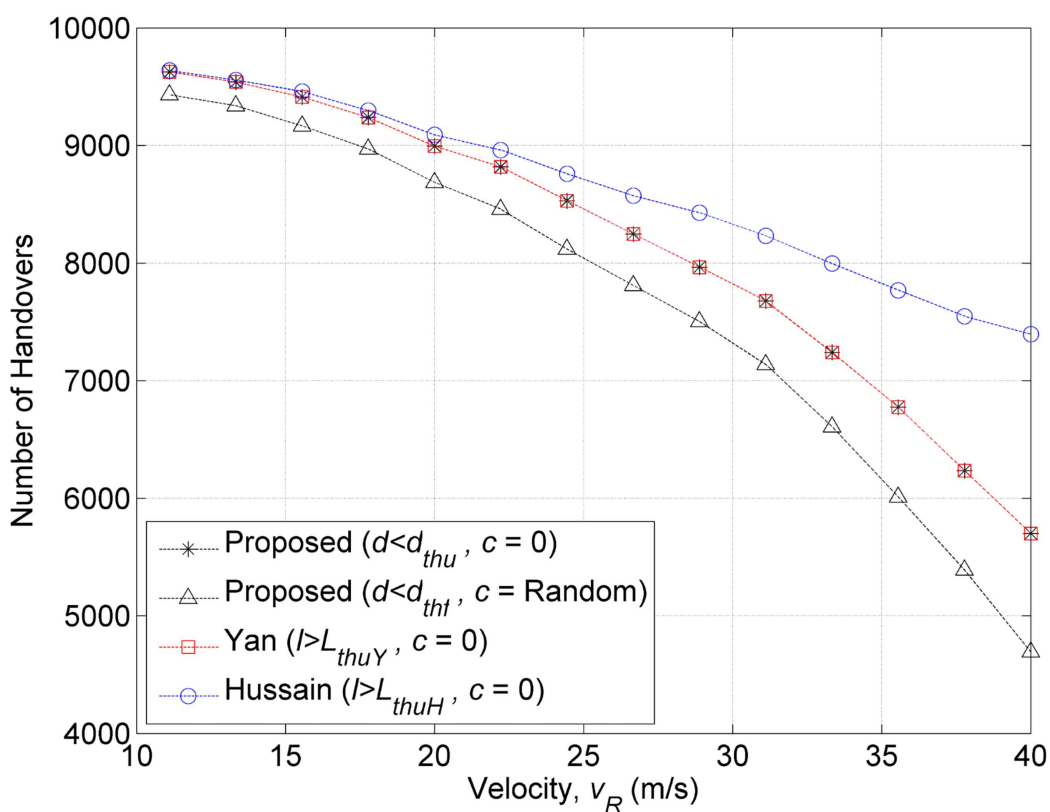
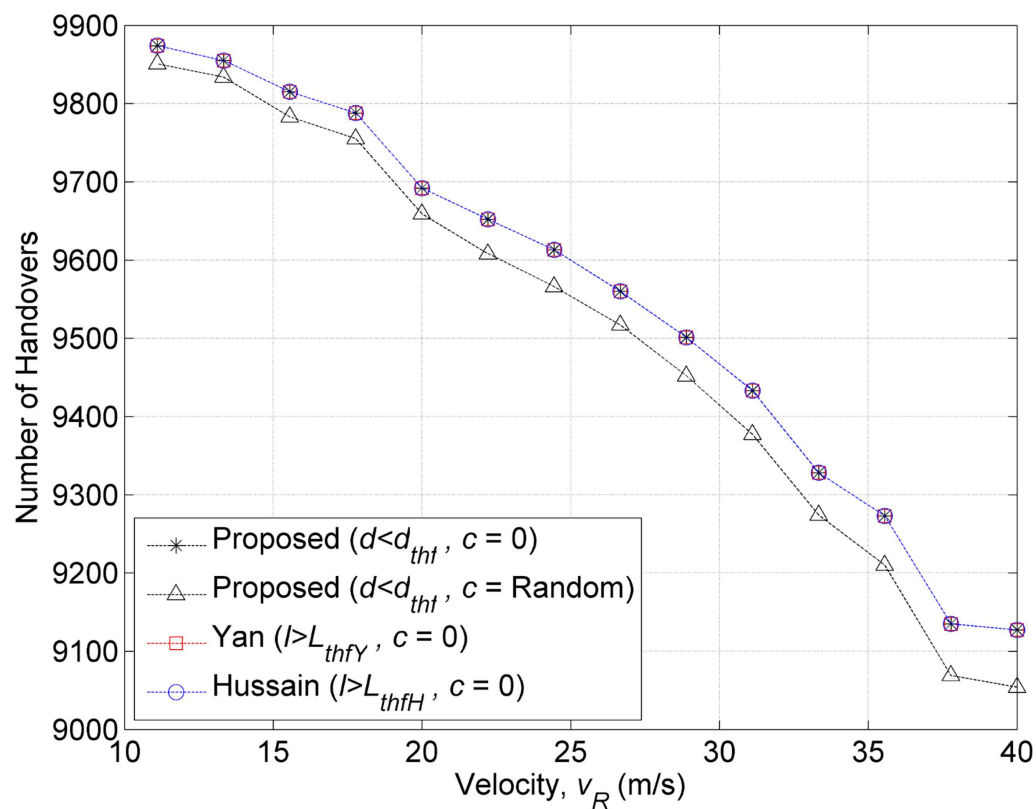
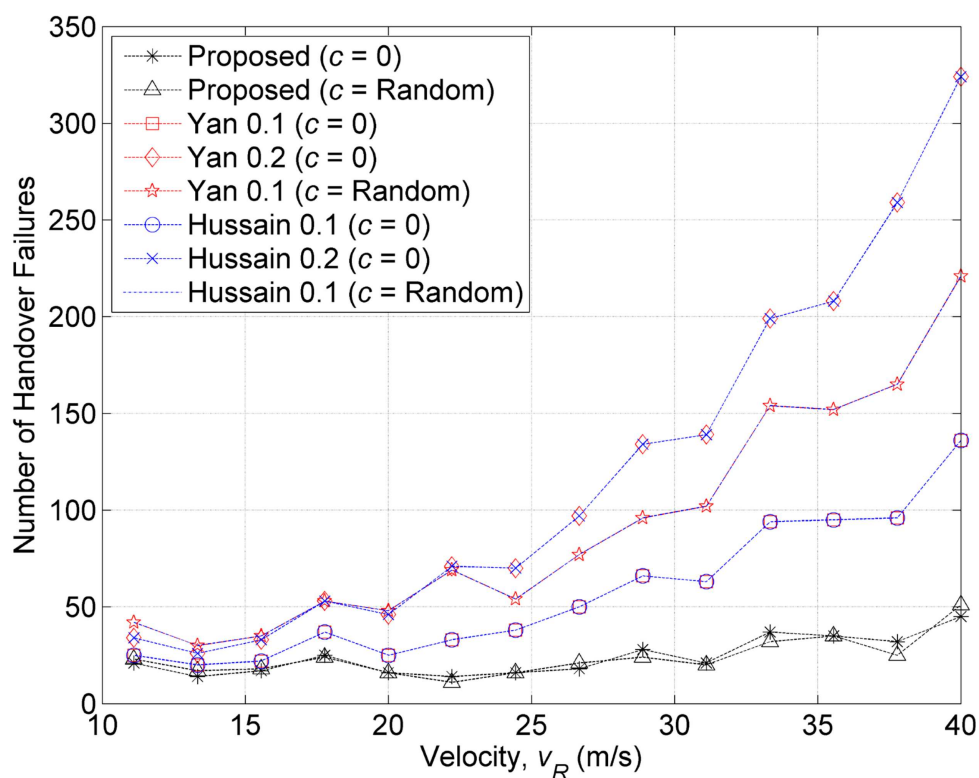


Fig 5. Total number of handovers to the WLAN based on (A) handover failure threshold and (B) unnecessary handover threshold.

doi:10.1371/journal.pone.0165888.g005

A.



B.

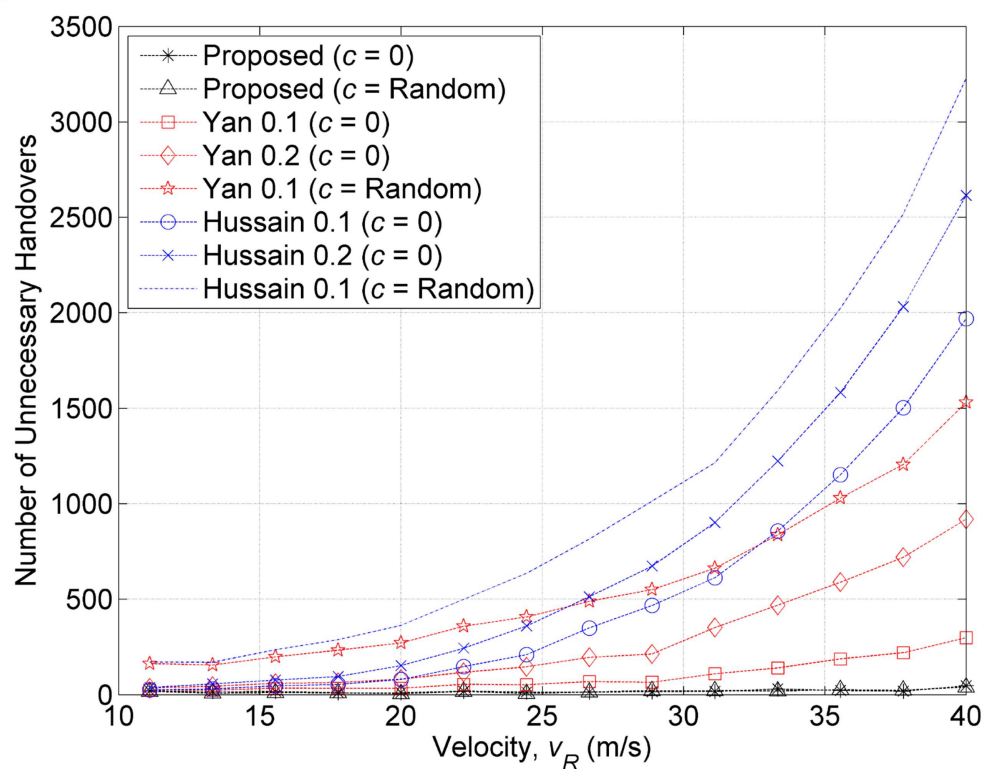
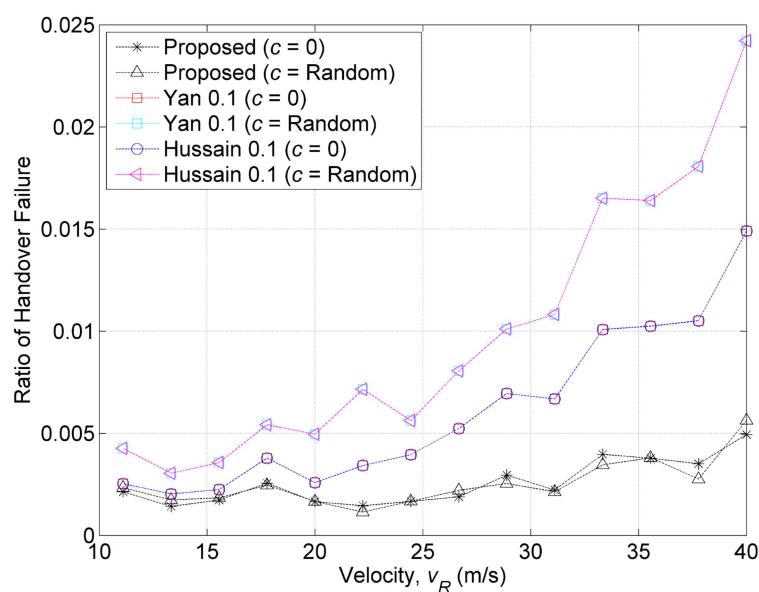


Fig 6. Number of (A) handover failures and (B) unnecessary handovers.

doi:10.1371/journal.pone.0165888.g006

A.



B.

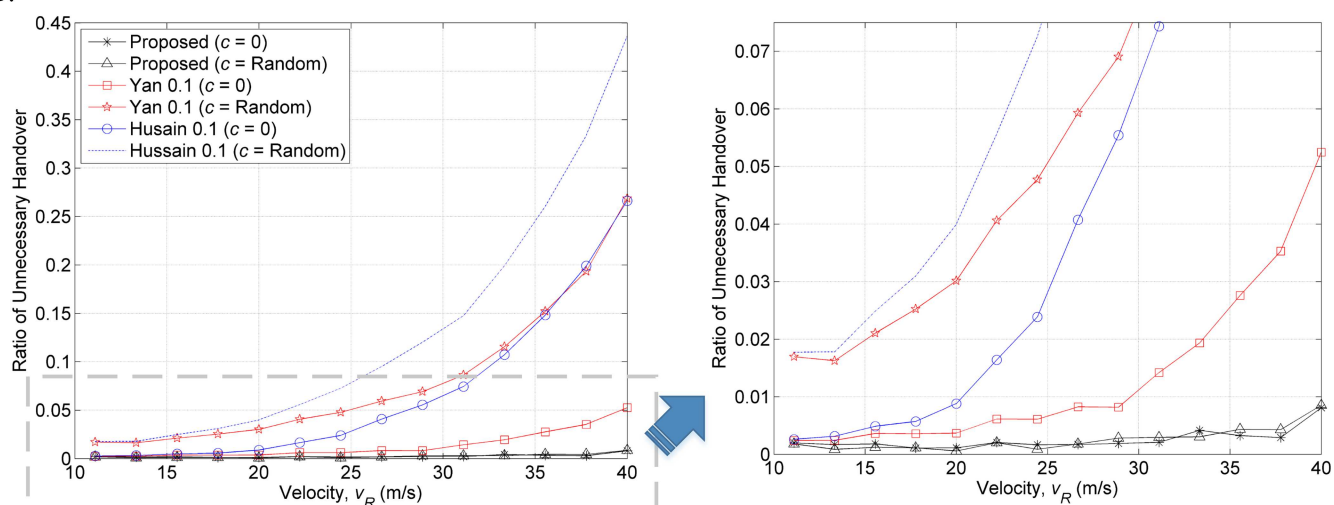


Fig 7. Ratio of (A) handover failures and (B) unnecessary handovers to the total number of handovers.

doi:10.1371/journal.pone.0165888.g007

speed affects the accuracy of RSS measurements and distance prediction. The summary of the performance comparison results is listed in Table 2. The results show that the proposed method has successfully reduced the probability of handover failures and unnecessary

Table 2. Summary of performance comparison.

Methods	Yan et al.[6]		Hussain et al.[15]		Proposed	
$t_s - t_{v_{InRSSth}}$ (s)	0.1	0.1	0.1	0.1	Not Applicable	Not Applicable
c (m/s ²)	0	Random	0	Random	0	Random
Ratio of the number of handover failures to the total number of handovers	< 0.015	< 0.025	< 0.015	< 0.025	< 0.005	< 0.005
Ratio of the number of unnecessary handovers to the total number of handovers	< 0.055	< 0.270	< 0.270	< 0.430	< 0.010	< 0.010

doi:10.1371/journal.pone.0165888.t002

handovers to the WLAN by up to 66.7% and 96.3% in first scenario ($c = 0$), and 80.0% and 97.7% in second the scenario ($c = 1 \sim 5 \text{ m/s}^2$) compared with the previous methods.

Conclusion

This paper has presented a new vertical handover method to optimize the utilization of WLAN in high-speed environment. The proposed method overcomes the imperfections and limitations of previous methods. The simulation results show that the proposed method performs better than the previous methods. It keeps the probability of handover failure and unnecessary handover below 0.5% and 1% respectively. The proposed method can be applied for all handovers from macro-cell, such as Long Term Evolution (LTE), Worldwide Interoperability for Microwave Access (WiMAX) or Universal Mobile Telecommunications System (UMTS) to WLAN. With the proposed method, the user can benefit more from WLAN cells with high bandwidth and low access cost, which can improve the quality of service and the cost effectiveness.

In future, we will focus on fast and robust authentication to further improve the performance of handover from macro-cell to WLAN in high mobility scenario. An efficient authentication scheme can minimize the handover latency, packet loss and communication overhead [24]. The recent authentication schemes and protocol designs can be found in [25–29].

Supporting Information

S1 Dataset. Data of simulation results. A: Relationship between the d , acceleration and velocity (Fig 2A). B: Relationship between d_{th} , acceleration and velocity (Fig 2B). C: Total number of handover to the WLAN based on the handover failure threshold (Fig 5A). D: Total number of handover to the WLAN based on the unnecessary handover threshold (Fig 5B). E: Number of handover failures (Fig 6A). F: Number of unnecessary handovers (Fig 6B). G: Ratio of handover failures to the total number of handovers (Fig 7A). H: Ratio of unnecessary handovers to the total number of handovers (Fig 7B). (XLSX)

Acknowledgments

This research is supported by the Ministry of Education Malaysia and Universiti Teknologi Malaysia under Grant No. Q.J130000.2745.02K17, R.J130000.7309.4B120, R.J130000.7309.4B121, R.J130000.7309.4B122, and R.J130000.7309.4B123.

Author Contributions

Conceptualization: HTY MHS ES.

Data curation: HTY MHS.

Formal analysis: HTY MHS.

Funding acquisition: MHS ES.

Investigation: HTY MHS.

Methodology: HTY MHS.

Project administration: HTY MHS ES YWH.

Resources: HTY MHS ES.

Software: HTY MHS.

Supervision: HTY MHS ES YWH.

Validation: HTY MHS.

Visualization: HTY MHS ES YWH.

Writing – original draft: HTY MHS ES YWH.

Writing – review & editing: HTY MHS ES YWH.

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