International Journal of Pervasive Computing and Comm

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Received 24 June 2014
Revised 18 September 2014
Accepted 22 January 2015

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Abstract

Purpose – The paper aims to propose an optimized handover necessity estimation scheme for a mobile terminal (MT) traversing from a third-generation (3G) cellular network into the wireless local area network (WLAN) cell for reducing the number of handover failures and unnecessary handovers.

Design/methodology/approach – The proposed optimized handover necessity estimation scheme comprises of two algorithms – a "travelling time prediction" reliant on consecutive received signal strength (RSS) measurements and MT's velocity, and a "time threshold estimation" depending on the handover latency, WLAN's cell radius, tolerable handover failure probability and the tolerable unnecessary handover probability.

Findings – Our performance analysis reveals that the suggested mechanism effectively minimizes the number of handover failures and unnecessary handovers by 60 per cent as compared to the already proposed schemes in the literature.

Originality/value – The convergence of Internet and wireless mobile communication accompanied by a massive increase in the number of cellular subscribers has led mobility management to emerge as a significant and challenging domain for wireless mobile communication over the Internet. Mobility management enables serving networks to locate roaming terminals for the call delivery (location management) and ensures a seamless connection as MT enters into the new service area (handover management). In this manuscript, an optimized handover necessity estimation scheme has been envisaged for reducing the probability of handover failures and unnecessary handovers from 3G cellular networks to WLANs to provide optimal network utilization along with an enhanced user satisfaction. Performance analysis reveals that the suggested scheme yields enhanced results as compared to the schemes already proposed in the literature.

Keywords Quality of service, Handover failure probability, Received signal strength, Vertical handover decisions

Paper type Research paper

1. Introduction

Over the recent past, wireless communication market has witnessed a considerable amount of intensification, both in aspects of mobile technology and subscribers, which has led network operators and vendors to apprehend the importance of efficacious networks along with an equally intelligent design processes (Hasswa *et al.*, 2007; Misra, 2013; Yan *et al.*, 2010). Wireless communication has today become ubiquitous; it has

International Journal of Pervasive Computing and Communications
Vol. 11 No. 1, 2015
pp. 2-16

1742-7371
DOI 10.1108/IJPCC-06-2014-0034

almost revolutionized every single aspect of our daily lives. The sheer increase in the number of cellular phones, mobile handheld devices, personal digital assistants and mobile subscribers has demanded upgradation of cellular communication technologies through several generations to cater demand for modern data services, multimedia services and voice communications (Agarwal *et al.*, 2011; Hussain *et al.*, 2012; Yan *et al.*, 2010).

Standardization work for third-generation (3G) wireless networks initiated in the late 1990s, wherein the fundamental perspective was to provide subscribers with a high-rate voice and data service along with the network security and reliability (i.e. 3G cellular network data rates for users in high-speed vehicles over large areas is 144, 384 kbps for pedestrians in slowly moving in small areas and 2,048 kbps for the indoor offices and stationary users). The aim of the 3G networks is to support an Internet protocol-based data, voice and multimedia services with integration to Internet to provide useful Internet applications to mobile users (Knisely *et al.*, 2002; Pereira, 2000; Mshvidobadze, 2012). Similarly, the improved interoperability to handle mobility across various radio technologies amongst different network providers is also a critical task for the 3G services. In contrast to preceding generations, 3G technology assisted network operators and service providers to offer users with a greater bandwidth, reliability and security, thus making it more appropriate for certain advanced applications such as mobile e-commerce, video-conferencing, video on demand, location-sensitive services (mobile programs to search for bars or restaurants), customized personal information services, etc. However, its major drawback lies in its associated high costs for both network operators and end-users due to the continuous upgradation of cellular infrastructure and soaring spectrum license costs (de la Oliva *et al.*, 2011; Dalal and Kosta, 2009).

Several network operators and organizations have varying views pertaining to fourth-generation (4G) networks. The Japanese predominant cellular operator NTT DoCoMo envisaged 4G by establishing a notion of MAGIC (mobile multimedia; anytime, anywhere and anyone; global mobility support; integrated wireless solution; and customized personal service) that particularly concentrates on public systems and regards 4G as an extension of the 3G cellular service (Frattasi *et al.*, 2006). This is also referred to as "*Linear 4G Vision*", which implies a future 4G network possessing only a cellular infrastructure with extremely high data rates of up to 100 Mb/s. In particular, this is present actual tendency in South Korea and China (Bauer, 2003). Nevertheless, if 4G is treated as the successor of earlier generations, it could not be only confined to cellular systems. European Commission recently offered a "*Concurrent 4G Vision*" – ensuring seamless service amongst a multitude of wireless systems and an optimum delivery via the most appropriate available network (Da Silva, 2000).

The International Telecommunication Union (ITU)'s Radiocommunication Sector is in the process of establishing a globally accepted and agreed definition of 4G in consultation with its diverse stakeholder groups. In this regard, several Working Party sessions have already been convened to discuss as to what should be encompassed in the nucleus of a 4G system, so that technologies in the near future could earn the right to be categorized into this group (3G Americas, 2008). By the mid-2008, ITU has explicitly specified the said 4G requirements, and at present, there are only two families of standards that fit the bill: 3rd Generation Partnership Project: Long-Term Evaluation standard and WiMAX. Though the high-speed packet access (HSPA) and the evolved

HSPA (HSPA+) are marketed by various network operators as 4G services in different parts of world, they are not considered 4G in the true sense.

In a typical 4G heterogeneous networking environment, the *handover management process* (one of mobility management hierarchical components) should be able to opt for the most appropriate time to initiate the handover and a best accessible network to perform handover to (in an *always best connected mode*) (Taniuchi *et al.*, 2009). The vertical handoff decision (VHD) scheme thus becomes crucial in this regard, as it establishes when and at which network to perform handover amongst the accessible network candidates (in a heterogeneous wireless environment) so as to guarantee the session continuity. The IEEE has recently catered for this problem space/domain of seamless inter-system handovers by releasing a promising standard, also referred to as the *IEEE 802.21 Media Independent Handover (MIH)*, that accounts for handovers in both wired and wireless technologies, including *802.3, 802.11, 802.15, 802.16, 3GPP and 3GPP2*. However, implementation of VHD algorithms is still out of the scope of the IEEE 802.21 framework, and is left for the consideration of the system designers (Hossain, 2008).

In this manuscript, an optimized VHD algorithm has been envisaged for reducing probability of handover failures and unnecessary handovers from 3G cellular networks to wireless local area network (WLANs) to provide optimal network utilization along with an enhanced user satisfaction. Performance analysis reveals that the suggested scheme yields enhanced results as compared to the schemes already proposed in the literature.

2. Literature review

Existing literature cites numerous studies pertinent to VHD algorithms. In Mohanty (2006), a mechanism for computing the dynamic boundary area depending on velocity of mobile terminal (MT) and WLAN cell dimension has been presented, wherein handover(s) from the WLAN to a 3G cellular system is instigated as soon as the MT penetrates the WLAN boundary and the handover process is accomplished before MT exits the WLAN area. This is also true for mobility architectures put forward in Varma *et al.* (2003) and Liu *et al.* (2008). The said mechanisms are though quite effective for handoffs commencing from WLAN to a 3G network; nonetheless, it is not considered efficacious for handoffs commencing from a 3G to the WLAN. Primary problem with these all schemes is that they lean to actuate handovers to a low-cost/high-throughput WLANs – as and when its coverage is accessible. However, in situations where MT propagates through an area quite near to WLAN periphery with speeds above a particular threshold, handovers to WLAN will ultimately result in the network resource wastage and degradation of MT's battery life. Moreover, if handover process is not accomplished before MT moves out of the WLAN boundary, a connection failure becomes unavoidable (Chang and Leu, 2004; Chen and Shu, 2005).

In Hussain *et al.* (2013), a VHD algorithm is suggested to minimize the amount of handover failures and unnecessary handovers based on dwell time estimation and computation of threshold values for a MT traversing from a 3G network into the WLAN cell; however, it also proved quite ineffective for speeds above 30 km/h (Mahmood *et al.*, 2014; Mahmood *et al.*, 2015). A similar geometrical framework has been illustrated in Yan *et al.* (2008a, 2008b) and Yan (2010) for minimizing probabilities of handover failures and unnecessary handovers based on MT's angle of arrival and angle of departure; however, the absolute interior difference between angles is erroneously considered between [0 and 2π] by the authors', which thus resulted in mathematical imperfections for the estimation of the distance (threshold) parameters (Hussain *et al.*, 2013; Hussain *et al.*, 2012).

This manuscript is an attempt to construct on earlier works (Mahmood *et al.*, 2014; Mahmood *et al.*, 2015; Hussain *et al.*, 2013; Yan *et al.*, 2008a, 2008b and Yan, 2010) so as to eradicate the mathematical imperfections and to suggest an optimized mechanism for reducing the amount of handover failures and unnecessary handovers.

3. Proposed mechanism

3.1 Travelling time prediction based on the consecutive RSS measurements[1]

The proposed handover necessity estimation mechanism hinges on an algorithm that seeks to anticipate travelling time in a WLAN boundary/coverage by utilizing consecutive Received Signal Strength (RSS) measurements. The algorithm presumes that the WLAN cell possesses a circular contour, MT propagates from the WLAN coverage in a straight course with a uniform velocity, and the empirical model used for the propagation environment is the log-distance path loss model. The said scenario is depicted in the Figure 1.

The travelling time estimation of MT based on successive RSS measurements is calculated in subsequent manner. It is presumed that the MT receives considerably powerful signal at point A, while signal intensity lowers from the serviceable level at the

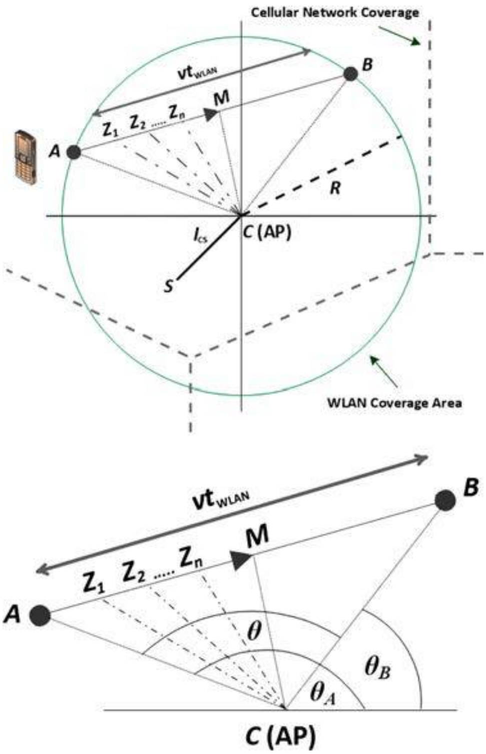

Figure 1.
Travelling time prediction scenario in a WLAN cell

point B (i.e. as soon as MT "enters" and "exits", the WLAN exposure area). M is middle point of MT's travelling path. As MT approaches the WLAN coverage at time t_A, the distance l_{CA}, which is approximately equivalent to the radius R, is measured through the log-distance path loss model as:

$$\mathrm{RSS}_A = P_{Tx} - \mathrm{PL}_{\mathrm{ref}} - \frac{10\gamma \log_{10} l_{CA}}{d_{\mathrm{ref}}} + X_\sigma \tag{1}$$

$$R \cong l_{CA} = d_{\mathrm{ref}} 10^{\frac{P_{\mathrm{Tx}} - \mathrm{PL}_{\mathrm{ref}} - \mathrm{RSS}_A - X_\sigma}{10\gamma}} \tag{2}$$

where RSS_A refers to RSS at the entry point of a WLAN coverage area, P_{Tx} refers to WLAN access point's (AP) transmit power in dBm, $\mathrm{PL}_{\mathrm{ref}}$ relates to path loss at reference point, d_{ref} is the stretch amongst C and the reference point, γ refers to a path loss exponent, while X_σ refers to normally distributed random variable (i.e. Gaussian) having a zero mean and σ standard deviation in dB (*in case of shadow fading or slow fading*).

To predict the travelling time t_{WLAN}, MT obtains consecutive RSS samples at the points $Z_1, Z_2, \ldots, Z_n$ at times $t_{z_1}, t_{z_2}, \ldots, t_{z_n}$, respectively. The change in RSS is depicted as:

$$\Delta \mathrm{RSS}_Z = \left| \frac{\mathrm{RSS}_{Z_n} - \mathrm{RSS}_{Z_{(n-1)}}}{t_{Z_n} - t_{Z_{(n-1)}}} \right| \tag{3}$$

By using equation (2), the distance between C and Z_n ($n = 1, 2, 3, [\ldots]$), i.e. l_{CZ_n}, is projected by[2]:

$$l_{CZ_n} = d_{\mathrm{ref}} 10^{\frac{P_{\mathrm{Tx}} - \mathrm{PL}_{\mathrm{ref}} - \Delta \mathrm{RSS}_Z + X\sigma}{10\gamma}} \tag{4}$$

By geometric arrangements of Figure 1, following equations are thus obtained:

$$l_{AM}^2 + l_{CM}^2 = l_{CA}^2 = R^2 \tag{5a}$$

$$l_{CM}^2 + l_{Z_nM}^2 = l_{CZ_n}^2 \tag{5b}$$

$$l_{Z_nM} = l_{AM} - l_{AZ_n} \tag{5c}$$

where l_{AM}, l_{CM}, l_{Z_nM}, l_{CZ_n} and l_{AZ_n} are stretches amongst entrance point A and the central point M, APs locality C and M, the sample point Z_n and M, point C and Z_n, as well as the point A and Z_n, correspondingly.

By substituting equation (5c) in equation (5b), the following mathematical expression transpires:

$$l_{CM}^2 + (l_{AM} - l_{AZ_n})^2 = l_{CZ_n}^2 \tag{6}$$

Consider v as a uniform speed of MT during time interval t, while the MT travels through WLAN cell exposure area:

$$l_{AM} = \frac{vt_{\mathrm{WLAN}}}{2} \tag{7a}$$

$$l_{AZ_n} = v(t_{Z_n} - t_A) \tag{7b}$$

where t_{Z_n} and t_A refers to the sampling time at point Z_n and entry point A. By substituting equation (7) in equations (5a) and (6), we acquire:

$$\left(\frac{vt_{\mathrm{WLAN}}}{2}\right)^2 + l_{CM}^2 = R^2 \tag{8a}$$

$$l_{CM}^2 = R^2 - \left(\frac{vt_{\mathrm{WLAN}}}{2}\right)^2 \tag{8b}$$

$$l_{CM}^2 + \left[\frac{vt_{\mathrm{WLAN}}}{2} - v(t_{Z_n} - t_A)\right]^2 = l_{CZ_n}^2 \tag{9a}$$

$$R^2 - \left(\frac{vt_{\mathrm{WLAN}}}{2}\right)^2 + \left[\frac{vt_{\mathrm{WLAN}}}{2} - v(t_{Z_n} - t_A)\right]^2 = l_{CZ_n}^2 \tag{9b}$$

$$R^2 + v^2(t_{Z_n} - t_A)^2 - (vt_{\mathrm{WLAN}})v\left(t_{Z_n} - t_A\right) = l_{CZ_n}^2 \tag{9c}$$

Based on equation (9c), estimate for travelling time is obtained as follows:

$$t_{\mathrm{WLAN}} = \frac{R^2 - l_{CZ_n}^2 + v^2(t_{Zn} - t_A)^2}{v^2(t_{Zn} - t_A)} \tag{10}$$

$$t_{\mathrm{WLAN}} = \frac{d_{\mathrm{ref}}10^{\frac{2(\mathrm{P_{Tx}} - \mathrm{PL_{ref}} - \mathrm{RSS}_A + X\sigma)}{10\gamma}} - d_{\mathrm{ref}}10^{\frac{2(\mathrm{P_{Tx}} - \mathrm{PL_{ref}} - \Delta\mathrm{RSS}_Z + X\sigma)}{10\gamma}} + v^2(t_{Zn} - t_A)^2}{v^2(t_{Zn} - t_A)} \tag{11}$$

The MT's travelling speed "v" can be estimated by using an accelerometer installed within the MT (Zhu and Lamarche, 2007).

3.2 Time threshold estimation for minimizing/reducing of the handover failures

The rationale behind *time threshold estimation algorithm* suggested here is to maintain the amount of handover failures under an acceptable limit. It is presumed that A and B can be any randomly selected entry and exit locations on boundary enfolding the WLAN exposure, and possessing an identical probability (Figure 1). The angles θ_A and θ_B are evenly dispersed within the range [0 to π] with $\theta = |\theta_A - \theta_B|$.

The probability density function (PDF) of the locations A and B are derived, respectively, as:

$$f_A(\Theta_A) = \begin{cases} \frac{1}{\pi}, & 0 \leq \Theta_A \leq \pi, \\ 0, & \text{otherwise}, \end{cases} \tag{12}$$

$$f_B(\Theta_B) = \begin{cases} \frac{1}{\pi}, & 0 \le \Theta_B \le \pi, \\ 0, & \text{otherwise.} \end{cases} \tag{13}$$

Because A and B are independent of one another, their joint PDF is computed as:

$$f_{A,B}(\Theta_A, \Theta_B) = \begin{cases} \frac{1}{\pi^2}, & 0 \le \Theta_A, \Theta_B \le \pi, \\ 0, & \text{otherwise.} \end{cases} \tag{14}$$

The probability that $\theta \le \Theta$ (also referred to as the *cumulative distributive function [CDF]* of θ) can be computed from the integral suggested in Mohanty (2006) and Bettstetter *et al.* (2004) as:

$$F_\theta(\Theta) = P(\theta \le \Theta) = \iint_\Omega f(\theta_A, \theta_B)\, d\theta_B\, d\theta_A \tag{15}$$

where Ω is the stretch amongst WLAN entry point A and exit point B, such that $\theta \le \Theta$ and $\theta \le \Theta \le \pi$. $P(\theta \le \Theta) = 0$ for $\Theta < 0$ and $P(\theta \le \Theta) = 1$ for $\Theta > \pi$. By observation, the equation (15) can be rewritten as:

$$F_\theta(\Theta) = \frac{1}{\pi^2}\left[\int_0^\Theta \int_0^{\Theta+\theta_A} d\theta_B d\theta_A + \int_\Theta^{\pi-\Theta} \int_{\theta_A-\Theta}^{\Theta+\theta_A} d\theta_B d\theta_A + \int_{\pi-\Theta}^{\pi} \int_{\theta_A-\Theta}^{\pi} d\theta_B d\theta_A\right.$$

$$F_\theta(\Theta) = \frac{1}{\pi^2}\left[\frac{3\Theta^2}{2} + 2\Theta\pi - 4\Theta^2 + \frac{3\Theta^2}{2}\right] = \frac{1}{\pi^2}[2\Theta\pi - \Theta^2]$$

$$F_\theta(\Theta) = \frac{2\Theta}{\pi} - \frac{\Theta^2}{\pi^2}, \quad 0 \le \Theta \le \pi \tag{16}$$

The PDF of θ can be measured from the derivative of equation (16) as follows[3]:

$$f_\theta(\Theta) = \begin{cases} \frac{2}{\pi}\left(1 - \frac{\Theta}{\pi}\right), & 0 \le \Theta \le \pi, \\ 0, & \text{otherwise.} \end{cases} \tag{17}$$

The subsequent task is thus to utilize the PDF of θ along with travelling time t_{WLAN} to achieve PDF of t_{WLAN}. By the geometric relationship of Figure 1, we get:

$$(vt_{\text{WLAN}})^2 = 2R^2(1 - \cos\ \theta) \tag{18}$$

$$t_{\text{WLAN}} = \sqrt{\frac{2R^2}{v^2}(1 - \cos\theta)} = g(\theta) \tag{19}$$

Using the theorem presented in equation (5.5) by Papoulis and Pillai (2002), the PDF of t_{WLAN} is given as[4]:

$$f(T) = \frac{f(\theta_1)}{|g'(\theta_1)|} + \frac{f(\theta_2)}{|g'(\theta_2)|} + \ldots + \frac{f(\theta_n)}{|g'(\theta_n)|} \tag{20}$$

$$f(T) = \begin{cases} \dfrac{4v}{\pi\sqrt{4R^2 - v^2T^2}}, & 0 \leq T \leq \dfrac{2R}{v}, \\ 0, & \text{otherwise.} \end{cases} \tag{21}$$

The CDF of t_{WLAN} is obtained by computing the integral of equation (21) as:

$$F(T) = \begin{cases} 1, & \dfrac{2R}{v} < T, \\ \dfrac{4}{\pi}\arcsin\left(\dfrac{vT}{2R}\right), & 0 \leq T \leq \dfrac{2R}{v}. \end{cases} \tag{22}$$

To perform handover decisions, a time threshold parameter T_{hf} is established. Whenever the anticipated travelling time t_{WLAN} is more than T_{hf}, MT will commence a handover process. Similarly, a handover failure transpires if travelling time within the WLAN coverage is less as compared to the handover latency τ_i from a 3G cellular network to WLAN. By means of equation (22), the handover failure probability of the proposed mechanism using time threshold T_{hf} is specified as:

$$P_{hf} = \begin{cases} \dfrac{4}{\pi}\left[\arcsin\left(\dfrac{v\tau_i}{2R}\right) - \arcsin\left(\dfrac{vT_{hf}}{2R}\right)\right], & 0 \leq T_{hf} \leq \tau_i \\ 0, & \tau_i < T_{hf}, \end{cases} \tag{23}$$

For MT to estimate the T_{hf} value for a particular value of P_{hf}, when $0 < P_{hf} < 1$:

$$T_{hf} = \frac{2R}{v}\sin\left(\arcsin\left(\frac{v\tau_i}{2R}\right) - \frac{\pi}{4}P_{hf}\right) \tag{24}$$

To compute the value for T_{hf}, travelling speed and handover latency needs to be ascertained. For purpose of the study at hand, the values for v and τ_i have been assumed. However, it can also be ascertained by using accelerometers and the *modus operandi* described by Zhu and Lamarche (2007) and Mohanty and Akyildiz (2006).

3.3 Time threshold estimation for minimizing/reducing of the unnecessary handovers

Similar to the arguments built in Section *B*, another time threshold parameter T_{uh} is established to reduce the number of unnecessary handovers. An unnecessary handover transpires when the travelling time (t_{WLAN}) within the WLAN coverage is less as compared to the sum of handover time into (τ_i) and out of (τ_o) the WLAN cell.

By using equation (23), unnecessary handover probability is specified as:

$$P_{uh} = \begin{cases} \dfrac{4}{\pi}\left[\arcsin\left(\dfrac{v(\tau_i + \tau_o)}{2R}\right) - \arcsin\left(\dfrac{vT_{uh}}{2R}\right)\right], & 0 \leq T_{uh} \leq \tau_i + \tau_o, \\ 0, & \tau_i + \tau_o < T_{uh}. \end{cases} \tag{25}$$

For MT to estimate the T_{uh} value for a particular value of P_{uh}, when $0 < P_{uh} < 1$:

$$T_{uh} = \frac{2R}{v}\sin\left(\arcsin\left(\frac{v(\tau_i + \tau_o)}{2R}\right) - \frac{\pi}{4}P_{uh}\right) \tag{26}$$

Parameters T_{hf} and T_{uh} relies on the values of constants P_{hf} and P_{uh} opted by the system designers, and also on the values of v, R, τ_i and τ_o.

4. Performance analysis and discussion

MATLAB has been used for the simulations, which constructed 10,000 arbitrary MT courses across a WLAN cell exposure for speed(s) ranging between 1 and 100 km/h with equal increments of 1 km/h. An arbitrary entrance point of WLAN cell was chosen for the each course, and an evenly dispersed random angle (i.e. in the range of "0 to π") has been created for specifying the MT's trajectory.

For the fixed RSS threshold-based mechanism (Mohanty's, 2006 and Varma's *et al.*, 2003), a handover is triggered if RSS from the WLAN reaches a fixed threshold (RSS_{fixed}), and the handover failure and unnecessary handover probability is thus computed as:

$$P_{hf_{fixed}} = \begin{cases} 1, & v\tau_i > 2R_{fixed}, \\ \frac{2}{\pi}\arcsin\left(\frac{v\tau_i}{2R_{fixed}}\right), & 0 \le v\tau_i \le 2R_{fixed}, \end{cases} \tag{27}$$

$$P_{uh_{fixed}} = \begin{cases} 1, & v(\tau_i + \tau_o) > 2R_{fixed}, \\ \frac{2}{\pi}\arcsin\left(\frac{v(\tau_i + \tau_o)}{2R_{fixed}}\right), & 0 \le v(\tau_i + \tau_o) \le 2R_{fixed}. \end{cases} \tag{28}$$

where, R_{fixed} is the stretch amongst the AP of the WLAN cell and MT's location as and when the handover transpires in a WLAN cell, and is thus computed as:

$$R_{fixed} = \frac{E_t - RSS_{fixed}}{10\gamma} \tag{29}$$

Similarly, for the hysteresis-based mechanism (Liu's *et al.*, 2008), a handover is triggered when RSS from the WLAN cell is above a threshold (RSS_{hyst}) plus a hysteresis (h) (hysteresis is a constant which is introduced to avoid a ping-pong effect) – the handover failure and unnecessary handover probability is computed as:

$$P_{hf_{hyst}} = \begin{cases} 1, & v\tau_i > 2R_{hyst}, \\ \frac{2}{\pi}\arcsin\left(\frac{v\tau_i}{2R_{hyst}}\right), & 0 \le v\tau_i \le 2R_{hyst}, \end{cases} \tag{30}$$

$$P_{uh_{hyst}} = \begin{cases} 1, & v(\tau_i + \tau_o) > 2R_{hyst}, \\ \frac{2}{\pi}\arcsin\left(\frac{v(\tau_i + \tau_o)}{2R_{hyst}}\right), & 0 \le v(\tau_i + \tau_o) \le 2R_{hyst}. \end{cases} \tag{31}$$

here, R_{hyst} is the stretch amongst the AP of the WLAN cell and MT's location, as and when the handover transpires in a WLAN cell, and is thus computed as (E_τ here refers to the AP's transmit power):

$$R_{hyst} = \frac{E_t - RSS_{hyst} + h}{10\gamma} \quad (32)$$

Moreover, for the handover necessity estimation scheme (Hussain's *et al.*, 2013) based on the prediction of dwell time in a WLAN cell, the handover failure and unnecessary handover probability is calculated as:

$$P_{hf_{Dwell}} = \frac{2}{\pi}\left(\arctan\left(\frac{v\tau_i}{\sqrt{4R^2 - v^2\tau_i^2}}\right) - \arctan\left(\frac{vM}{\sqrt{4R^2 - v^2M^2}}\right)\right) \quad (33)$$

where,

$$M = \frac{2R\,k_f}{v\sqrt{1 + k_f^2}}$$

$$k_f = \tan\left[\arctan\left(\frac{v\tau_i}{\sqrt{4R^2 - v^2 - \tau_i^2}}\right)\right] - \frac{\pi P_{hf_{Dwell}}}{2}$$

$$P_{uh_{Dwell}} = \frac{2}{\pi}\left(\arctan\left(\frac{v\tau_T}{\sqrt{4R^2 - v^2 - \tau_T^2}}\right) - \arctan\left(\frac{vN}{\sqrt{4R^2 - v^2 - N^2}}\right)\right) \quad (34)$$

where,

$$N = \frac{2Rk_u}{v\sqrt{1 + k_u^2}}$$

$$k_u = \tan\left[\arctan\left(\frac{v\,\tau_T}{\sqrt{4R^2 - v^2 - \tau_T^2}}\right) - \frac{\pi P_{uh_{Dwell}}}{2}\right]$$

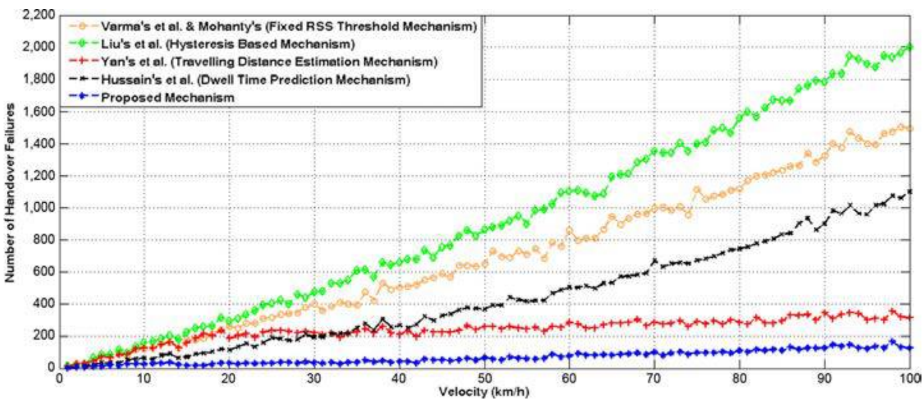

Figure 2.
Number of handover failures for fixed RSS threshold-based (Varma's *et al.* and Mohanty's), hysteresis-based (Liu's *et al.*), travelling distance estimation-based (Yan's *et al.*), dwell time prediction-based (Hussain's *et al.*) and proposed mechanisms

$$\tau_T = \tau_i + \tau_o$$

Furthermore, for the handover decision heuristic (Yan *et al.*, 2008a, 2008b and Yan, 2010) estimating MT's travelling distance in a WLAN coverage area, the handover failure and unnecessary handover probability is given as:

$$P_{hf_{Dist.}} = \begin{cases} \frac{2}{\pi}\left[\arcsin\left(\frac{v\tau_i}{2R}\right) - \arcsin\left(\frac{L1}{2R}\right)\right], & 0 \le L1 \le v\tau_i, \\ 0, & v\tau_i < L1, \end{cases} \quad (35)$$

$$P_{uh_{Dist.}} = \begin{cases} \frac{2}{\pi}\left[\arcsin\left(\frac{v(\tau_i + \tau_o)}{2R}\right) - \arcsin\left(\frac{L2}{2R}\right)\right], & 0 \le L2 \le v(\tau_i + \tau_o), \\ 0, & v(\tau_i + \tau_o) < L2. \end{cases} \quad (36)$$

Figures 2 and 3 exhibits the amount of handover failures and number of unnecessary handovers for the fixed RSS threshold, hysteresis-based, MT's dwell time prediction-based, MT's travelling distance estimation-based and the proposed optimized handover necessity estimation mechanisms, respectively. It can be illustrated from the simulations that the total

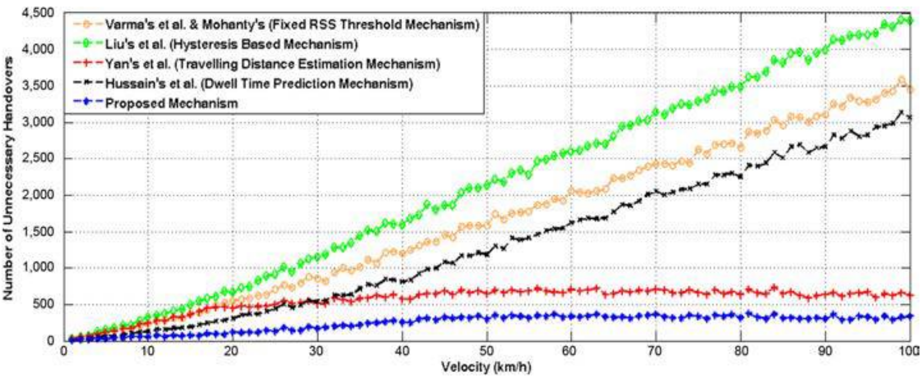

Figure 3. Number of unnecessary handovers for fixed RSS threshold-based (Varma's *et al.* and Mohanty's), hysteresis-based (Liu's *et al.*), travelling distance estimation-based (Yan's *et al.*), dwell time prediction-based (Hussain's *et al.*) and proposed mechanisms

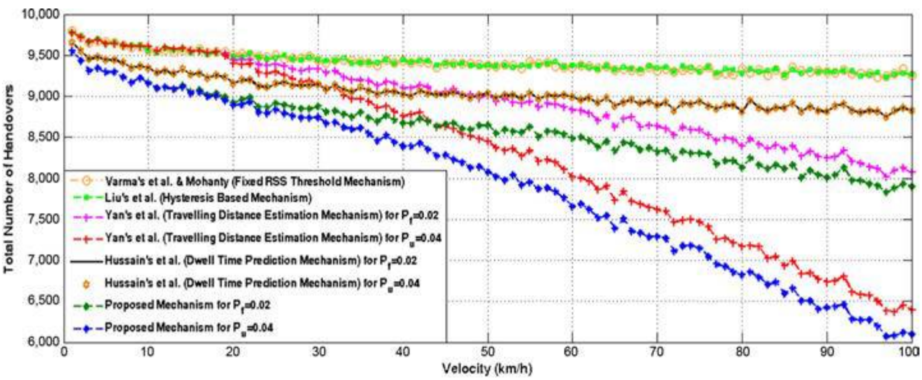

Figure 4. Total number of handovers for fixed RSS threshold-based (Varma's *et al.* and Mohanty's), hysteresis-based (Liu's *et al.*), travelling distance estimation-based (Yan's *et al.*), dwell time prediction-based (Hussain's *et al.*) and proposed mechanisms

number of handover failures and unnecessary handovers can be kept considerably low (i.e. less than approximately 200 and 400, respectively) for our proposed mechanism, and that the total number of handover failures and unnecessary handovers considerably decreases with an increase in velocity.

On the contrary, the number of handover failures and the unnecessary handovers significantly increases for fixed RSS threshold and hysteresis-based mechanisms with the increase in velocity. The number of handover failures and unnecessary handovers for MT's dwell time prediction-based mechanism remains comparatively low to fixed RSS threshold, hysteresis-based and MT's travelling distance estimation-based schemes for velocities up to approximately 30 km/h; however, it digresses by huge margins as compared to the MT's travelling distance estimation based mechanism at high velocities. The suggested scheme is efficaciously able to reduce the amount of handover failures and unnecessary handovers by 60 per cent as compared to the schemes already proposed in the literature.

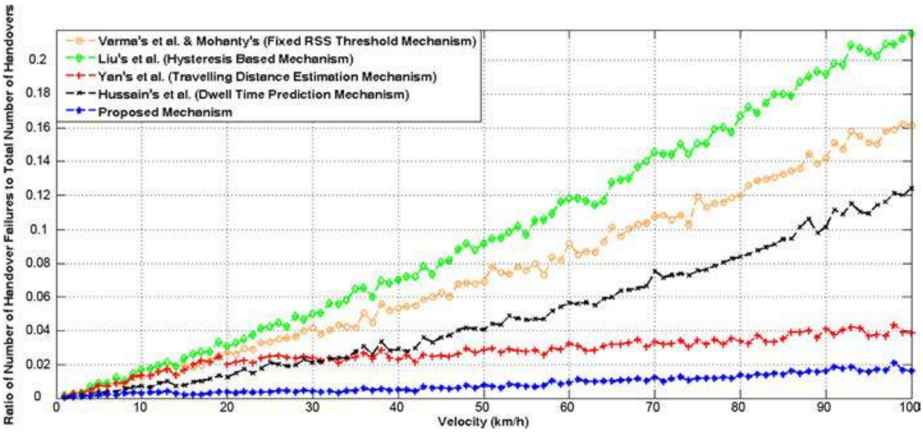

Figure 5. Ratio of number of handover failures *vis-à-vis* total number of handovers for fixed RSS threshold-based (Varma's *et al.* and Mohanty's), hysteresis-based (Liu's *et al.*), travelling distance estimation-based (Yan's *et al.*), dwell time prediction-based (Hussain's *et al.*) and proposed mechanisms

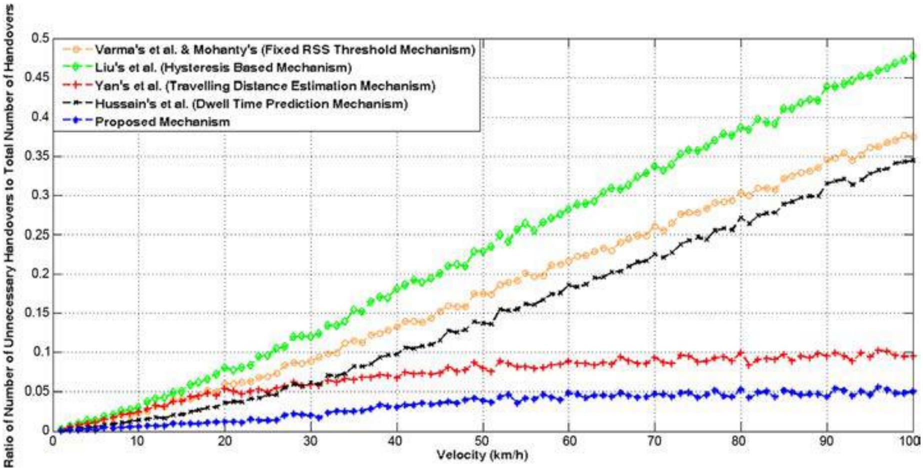

Figure 6. Ratio of number of unnecessary handovers *vis-à-vis* total number of handovers for fixed RSS threshold-based (Varma's *et al.* and Mohanty's), hysteresis-based (Liu's *et al.*), travelling distance estimation-based (Yan's *et al.*), dwell time prediction-based (Hussain's *et al.*) and proposed mechanisms

To provide a detailed illustration of performance analysis, the total number of handovers, ratio of number of handover failures *vis-à-vis* total number of handovers and the ratio of number of unnecessary handovers *vis-à-vis* the total number of handovers have been illustrated in Figures 4-6, respectively. This demonstrates that the said ratios can be kept around the tolerable values of handover failure probability and unnecessary handover probability (0.02 and 0.04, respectively).

Though mathematical expression(s) of proposed mechanism and that of Yan *et al.* (2008a, 2008b) and Yan (2010) and Hussain's *et al.* (2013) are nearly identical, their obtained threshold values gives simulation results that do not validate their respective assumptions and, therefore, results digress by huge margins. On the contrary, our simulation results approve our threshold values for keeping the handover failures and unnecessary handovers much below the desired level. The results presented in the manuscript also outperform our results deliberated by Mahmood *et al.* (2014) and Mahmood *et al.* (2015).

5. Future directions

A further enhancement in the proposed algorithm could be to periodically sample RSS, and to thus eliminate presumption that the MT's velocity remain uniform within the WLAN cell. Furthermore, the proposed scheme can be tuned by utilizing real propagation measurement data and applied to various realistic conditions. This would, in turn, lead to enhancement in the accurateness of performance evaluation, as WLANs are normally positioned in the urban areas that have significant shadow fading. Nevertheless, this is much beyond the scope of this manuscript.

Notes

1. Travelling time prediction has also been deliberated by Mahmood *et al.* (2014) and Mahmood *et al.* (2015), wherein an effort has been carried out to minimize the amount of handover failures and the unnecessary handovers.
2. If RSS_{Z_n} is smaller as compared to the $RSS_{Z_{(n-1)}}$, this implies that the MT has already passed through the middle of WLAN trajectory, and it will thus not attempt to switch to WLAN as it would not be staying for long enough in its coverage area.
3. In Yan *et al.* (2008a, 2008b) and Yan (2010), the mathematical expression illustrated for PDF of θ is: $f_\theta(\Theta) = 1/\pi(1-\Theta/2\pi), \quad 0 \leq \Theta \leq 2\pi$, wherein absolute interior difference angle is erroneously assumed in $[0, 2\pi]$, as θ can never be greater than π.
4. PDF of traversal time (in WLAN coverage area) obtained by Yan *et al.* (2008a, 2008b) and Yan (2010) was $f(T) = 2 \Big/ \pi\sqrt{4R^2-v^2T^2}, \quad 0 \leq T \leq 2R/v$.

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