Performance Analysis and Optimization of Handoff Algorithms in Heterogeneous Wireless Networks

Min Liu, *Member*, *IEEE*, Zhongcheng Li, *Member*, *IEEE*,
Xiaobing Guo, and Eryk Dutkiewicz, *Member*, *IEEE*

Abstract—The convergence of heterogeneous wireless access technologies with diverse levels of performance has been envisioned to characterize the next-generation wireless networks. In heterogeneous wireless networks, handoff can be separated into two parts: horizontal handoff (HHO) and vertical handoff (VHO). VHO plays an important role in fulfilling seamless data transfer when mobile nodes cross wireless access networks with different link layer technologies. Current VHO algorithms mainly focus on when to trigger VHO to improve connection QoS but neglect the problem of how one can synthetically consider all currently available networks (homogeneous or heterogeneous) and choose the optimal network for HHO or VHO from all available candidates. In this paper, we present an analytical framework to evaluate VHO algorithms. This framework can be used to provide guidelines for the optimization of handoff in heterogeneous wireless networks. Subsequently, we extend the traditional hysteresis-based and dwelling-timer-based algorithms to support both VHO and HHO decisions and apply them to complex heterogeneous wireless environments. We refer to these enhanced algorithms as E-HY and E-DW, respectively. Based on the proposed analytical model, we provide a formalization definition of the handoff conditions in E-HY and E-DW and analyze their performance. Subsequently, we propose a novel general handoff decision algorithm GHO to trigger HHO and VHO in heterogeneous wireless networks at the appropriate time. Analysis shows that GHO can achieve better performance than E-HY and E-DW. Simulations validate the analytical results and verify that GHO outperforms traditional algorithms in terms of the matching ratio, TCP throughput, and UDP throughput.

Index Terms—Heterogeneous wireless networks, vertical handoff, horizontal handoff.

1 Introduction

The convergence of heterogeneous wireless access technologies with diverse levels of performance has been envisioned to characterize the next-generation wireless networks (4G). Recent trends indicate that Wireless Wide Area Networks (WWANs) and Wireless Local Area Networks (WLANs) can coexist to complement their different characteristics and provide both universal coverage and broadband access to users.

Mobility management is a main challenge in the converged network. It addresses two main problems: location management and handoff management [1]. Location management tracks the mobile terminal for successful information delivery. Handoff management maintains the active connections for roaming mobile terminals as they change their point of attachment to the network. In this paper, we focus on handoff management.

- *M. Liu and Z. Li are with the Key Lab of Network Science, Institute of Computing Technology, Chinese Academy of Sciences, No.6 Ke Xue Yuan South Road, Haidian District, Beijing 2704 mailbox, 100190, P.R. China. E-mail: {liumin, zcli}@ict.ac.cn.*
- *X. Guo is with the Collaborative Computing Lab, Lenovo Corporate Research & Development, No.6 Shang Di West Road, Haidian District, Beijing, 100085, P.R. China. E-mail: guoxba@lenovo.com.*
- *E. Dutkiewicz is with the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Wollongong, NSW 2522, Australia. E-mail: eryk@uow.edu.au.*

Manuscript received 7 Feb. 2007; revised 27 June 2007; accepted 17 Sept. 2007; published online 3 Oct. 2007.
For information on obtaining reprints of this article, please send e-mail to: tmc@computer.org, and reference IEEECS Log Number TMC-0043-0207.
Digital Object Identifier no. 10.1109/TMC.2007.70768

Handoff (HO) is the mechanism by which an ongoing connection between a mobile terminal or mobile host (MH) and a correspondent terminal or correspondent host (CH) is transferred from one point of access to the fixed network to another [2]. In cellular networks, such points of attachment are referred to as base stations (BSs), and in WLANs, they are called access points (APs).

In heterogeneous wireless networks, handoff can be separated into two parts: horizontal handoff (HHO) and vertical handoff (VHO). A *horizontal handoff* is made between different access points within the same link-layer technology such as when transferring a connection from one BS to another or from one AP to another. A *vertical handoff* is a handoff between access networks with different link-layer technologies, which will involve the transfer of a connection between a BS and an AP.

Seamless and efficient VHO between different access technologies is an essential and challenging problem in the development toward the next-generation wireless networks. In general, the VHO process can be divided into three main steps: system discovery, handoff decision, and handoff execution [24]. During the system discovery phase, mobile terminals equipped with multiple interfaces have to determine which networks can be used and the services available in each network. During the handoff decision phase, the mobile device determines which network it should connect to. During the handoff execution phase, connections need to be rerouted from the existing network to the new network in a seamless manner. During the VHO procedure, the handoff decision is the most important step that affects MH's communication [11]. An incorrect handoff decision may degrade the QoS of traffic and even break off current communication.

Handoff algorithms in heterogeneous wireless networks should support both HHO and VHO and can trigger HHO or VHO based on the network condition. What should be noted is that, because of the uncertainty of the network distribution and the randomness of MH's mobility, it is impossible to forecast the type of the next handoff in advance. Thus, handoff algorithms in heterogeneous wireless networks must make the appropriate handoff decision based on the network metrics in a related short time scale.

In this paper, we present an analytical framework to evaluate VHO decision algorithms, which can be used to provide guidelines for the optimization of handoff in heterogeneous wireless networks. Then, we extend the traditional hysteresis-based and dwelling-timer-based algorithms to support both VHO and HHO decisions and apply them to complex heterogeneous wireless environments. We refer to these enhanced algorithms as E-HY and E-DW, respectively. Based on the proposed analytical model, we provide a formalization definition of the handoff conditions in E-HY and E-DW and analyze their performance. Subsequently, we propose an efficient general handoff decision algorithm GHO to select the optimal network for HHO or VHO from all available candidates at the appropriate time. Analysis shows that GHO can achieve better performance than E-HY and E-DW. Simulations validate the analytical results and verify that GHO outperforms traditional algorithms in terms of the matching ratio (MR), TCP throughput, and UDP throughput.

The remainder of this paper is structured as follows: Section 2 summarizes related work on handoff decision algorithms in heterogeneous wireless networks. Section 3 provides the assumptions used in this paper and presents the evaluation criteria for VHO algorithms. Section 4 introduces the architecture of our handoff management system. Section 5 presents the analytical framework for the evaluation of VHO algorithms. Section 6 extends the traditional hysteresis-based and dwelling-timer-based algorithms to support both VHO and HHO decisions and analyzes their performance. Section 7 proposes a novel VHO decision algorithm GHO and analyzes its performance. Section 8 verifies the feasibility and effectiveness of GHO and compares its performance with conventional algorithms. This paper is concluded in Section 9.

2 Related Work

There are three strategies for handoff decision mechanisms: mobile-controlled handoff (MCHO), network-controlled handoff (NCHO), and mobile-assisted handoff (MAHO) [2]. MCHO is used in IEEE 802.11 WLAN networks, where an MH continuously monitors the signal of an AP and initiates the handoff procedure. NCHO is used in cellular voice networks where the decision mechanism of handoff control is located in a network entity. MAHO has been widely adopted in the current WWANs such as GPRS, where the MH measures the signal of surrounding BSs and the network then employs this information and decides whether or not to trigger handoff. During VHO, only MHs have the knowledge about what kind of interfaces they are equipped with. Even if the network has this knowledge, there may be no way to control another network that the MH is about to hand off to. Therefore, MCHO and further assistance from the networks is more suitable for VHO [10].

Two main categories of handoff algorithms are proposed in the research literature [3] based on 1) the threshold comparison of one or more metrics and 2) dynamic programming (DP)/artificial intelligent techniques applied to improve the accuracy of the handoff procedure.

The first category is the traditional algorithms widely used in radio cellular systems, which employs a threshold comparison of one or several specific metrics to make a handoff decision. The most common metrics are received signal strength (RSS), carrier-to-interference ratio (CIR), signal-to-interference ratio (SIR), and bit error rate (BER) [2]. In heterogeneous wireless networks, even though the functionalities of access networks are different, all the networks use a specific signal (beacon, BCCH, or reference channel) with a constant transmit power to enable RSS measurements. Thus, it is very natural and reasonable for VHO algorithms to use RSS as the basic criterion for handoff decisions.

In order to avoid the ping-pong effect, additional parameters such as hysteresis and dwelling timer can be used solely or jointly in the handoff decision process. In [4], in addition to the absolute RSS threshold, a relative RSS hysteresis between the new BS and the old BS is added as the handoff trigger condition to decrease unnecessary handoffs. Marichamy et al. [5] proposes a handoff scheme based on RSS with the consideration of thresholds and hysteresis for mobile nodes to obtain better performance. However, in heterogeneous wireless networks, RSS from different networks can vary significantly due to different techniques used in the physical layers and cannot be easily compared with each other. Thus, the methods in [4] and [5] cannot be applied to VHO directly. Hatami et al. [6] use the dwelling timer as a handoff initiation criterion to increase the WLAN utilization. It was shown in [7] that the optimal value for the dwelling timer varies along with the used data rate or, to be more precise, with the effective throughput ratio. In [8], Ylianttila et al. extend the simulation framework in [6] by introducing a scenario for multiple radio network environments. Their main results show that the handoff delay caused by frequent handoff has a much bigger degrading effect for the throughput in the transition region. In addition, the benefit that can be achieved with the optimal value of the dwelling timer as in [7] may not be enough to compensate for the effect of handoff delay. In [9], Park et al. propose a similar dwelling-timer-typed approach by performing the VHO if a specific number of continuous received beacons from the WLAN exceed or fall below a predefined threshold. Additionally, in the real-time service, the number of continuous beacon signals should be lower than that of the non-real-time service in order to reduce the handoff delay.

More parameters may be employed to make more intelligent decisions. Lee et al. [10] propose a bandwidth-aware VHO technique which considers the residual bandwidth of a WLAN in addition to RSS as the criterion for handoff decisions. However, it relies on the QBSS load defined in the IEEE 802.11e Standard to estimate the residual bandwidth in the WLAN. In [11], McNair et al. propose a method for defining the handoff cost as a function of the available bandwidth and monetary cost. In

[12], actual RSS and bandwidth were chosen as two important parameters for the cost function. Chang et al. [13] propose an adaptive cost-based with predictive RSS approach to perform VHO in heterogeneous wireless networks. One main difficulty of the cost approach is its dependence on some parameters that are difficult to estimate, especially in large cellular networks. Mohanty and Akyildiz [14] developed a cross-layer (Layer 2 + 3) handoff management protocol CHMP, which calculates a dynamic value of the RSS threshold for handoff initiation by estimating MH's speed and predicting the handoff signaling delay of possible handoffs.

The second category of handoff algorithms use dynamic programming (DP) [15] or artificial intelligence techniques such as pattern recognition [16], [17], neural networks [2], or fuzzy logic [3], [18], [19] to improve the accuracy and effectiveness of the handoff procedure. Veeravalli and Kelly [15] pose the handoff problem as a finite-horizon DP problem and obtain the optimal solution through a set of recursive equations. The optimal solution is complicated and nonstationary, and it requires prior knowledge of the MH's exact trajectory. Subsequently, Veeravalli and Kelly [15] derive a simple locally optimal algorithm from the DP solution, which can be designed to be independent of the location of the MH. In [16], pattern-recognition-based handoff algorithms train a system using available metrics (for example, RSS) and the locations where handoff should be made so that the system acquires knowledge of the RSS patterns at such locations. Pahlavan et al. [2] present a simple neural-network-based approach to detect signal decay and make handoff decisions. Guo et al. [19] propose an adaptive multicriteria VHO (AMVHO) decision algorithm. This algorithm uses a fuzzy inference system (FIS) and a modified Elman neural network (MENN). The FIS adopts crucial criteria of the VHO as the input variables and makes the handoff decision based on the defined rule base. The MENN helps in the prediction for the number of users in the after-handoff network, which is a pivotal variable of the FIS.

It is important to mention that the complexity of such artificial-intelligence-based algorithms is very high, and its implementation in MHs with limited computing and storage capability may not be possible. In addition, training of the neural network has to be done beforehand.

To sum up, the application scenario of current VHO algorithms is relatively simple. For example, most VHO algorithms only consider the pure VHO scenario, where the algorithm only needs to decide when to use a 3G network and when to use a WLAN [1], [10], [19], [20], [21]. In fact, at any moment, there may be many available networks (homogeneous or heterogeneous), and the VHO algorithm has to select the optimal network for HHO or VHO from all the available candidates. For example, if the current access network of MH is a WLAN, the MH may sense many other WLANs and a 3G network at a particular moment, and it has to decide whether to trigger HHO or VHO. If the HHO trigger is selected, MH then needs to decide which WLAN is the optimal one. Consequently, an analytical framework to evaluate VHO algorithms is needed to provide guidelines for optimization of handoff in heterogeneous wireless networks. It is also necessary to build reasonable and typical simulation models to evaluate the performance of VHO algorithms.

3 Assumption and Evaluation Criteria

3.1 Assumption

As mentioned earlier, MCHO and further assistance from the networks is more suitable for VHO. Thus, we assume that the VHO algorithms take the MCHO strategy for handoff decisions, and the network environment satisfies the following conditions (note that we take 3G and IEEE 802.11b WLANs as representative examples of WWAN and WLAN, respectively; however, the proposed analytical framework and handoff algorithms are readily extendible to heterogeneous wireless networks formed by other WWANs and WLANs):

- Neither the WLAN nor the 3G network has network mobility [22]. In other words, the entire network, as a unit, does not change its point of attachment to the Internet and its reachability in the topology.
- Neither the signal strength of the WLAN nor the signal strength of the 3G network will change as time passes. In other words, the signal coverage area is stable.
- We assume that there is no height difference between the AP in a WLAN and the BS in a 3G network. This means that the AP and BS are located in the same 2D space, and the MH only moves in this 2D space.
- There is no object that influences or shelters the wireless signal in the range of MH's movement. There is no restriction on MH's movement either, which means that the MH can move in any direction with any speed.

In this paper, we do not consider the influence of the pricing model and user's special preferences for handoff. The purpose of handoff is to maintain the connection and achieve the best possible QoS.

3.2 Evaluation Criteria for Handoff Algorithms

In order to evaluate the performance of handoff algorithms, we have defined a new metric, *matching ratio*, in [23].

Matching means that the decision of the algorithm is the optimum access network at the moment. For example, when the 3G network could provide better QoS, it is said to be *matching* if the algorithm chooses the 3G network. The *matching ratio (MR)* is the percentage of the matching period per time unit. Higher *MR* means that the handoff algorithm can provide better QoS.

In addition to the *MR*, we also use TCP throughput and UDP throughput as evaluation criteria for handoff algorithms.

4 Architecture of Handoff Management System

Phalavan et al. made a summary of issues related to handoff [2]. These issues are divided into architectural issues and handoff decision algorithms. In this paper, we focus on the design and evaluation of handoff decision algorithms in heterogeneous wireless networks.

The fundamental aim of handoff is to make good use of network bandwidth and improve the QoS of applications. In Fig. 1, we show the general modules and procedures of

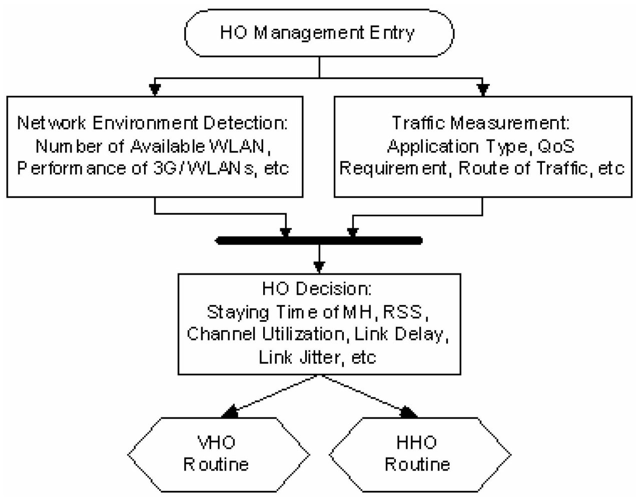


Fig. 1. The modules of handoff management system.

our system. Some of these modules collect the link-layer and network-layer information useful for handoff management, and other modules use this information to decide on the appropriate time to initiate handoff and execute the handoff procedures.

When the handoff management system starts, it will call the network environment detection module and traffic measurement module, respectively. The network environment detection module will try learning about the available access networks and their performance. For example, it will try finding out how many WLANs are currently available, their signal strengths, their availability, etc. At the same time, the traffic measurement module will judge the type of current applications and their QoS requirements. For example, it will consider whether the current application is a real-time application, determine its throughput or delay requirements, etc. In particular, the route of the traffic should also be considered. A typical case is when the source and destination are both in a 3G network. Staying in the 3G network will then be better than switching to WLAN to guarantee the QoS of this traffic.

If there are multiple network choices, and the current access network cannot satisfy the QoS requirements of the existing applications, the handoff decision module will be started. It will determine the destination network based on the staying time of the MH in the candidate networks and these networks' QoS estimation, including RSS, channel utilization, link delay/jitter, etc. Based on the output of the handoff decision algorithm, the system will choose to enter the VHO routine or the HHO routine or keep the current connection.

In order to reduce the complexity of the handoff algorithm, shorten the handoff decision process, and save the limited computing and storage capability of MH, in our current implementation, only the staying time of the MH and the RSS are considered in the handoff decision module.

5 Analytical Framework of Vertical Handoff Algorithms

During the handoff decision process, two factors should be considered. On one hand, the MH should try maximizing the utilization of a high bandwidth and low cost access network. On the other hand, the number of unnecessary handoffs should be minimized to avoid degrading the QoS of current communication and overloading the network with signaling traffic.

In VHO, the RSSs are incomparable due to VHO's asymmetrical nature. However, they can be used to determine the availability and the condition of the different networks. In real environments, a WWAN can be assumed to support global coverage in which WLAN segments are only small isolated islands. Thus, a great deal of research uses the RSS of the WLAN beacon as the basic criterion for handoff decisions in heterogeneous networks formed by a WWAN and WLANs [10].

Assume that a heterogeneous wireless network comprises a single 3G network and Q WLANs. The distance from the MH to the AP of $WLAN_i$ $(1 \le i \le Q)$ is d_i, and when $d_i = \varphi$, RSS_i (the RSS of $WLAN_i$) is equal to RSS_0 (the RSS threshold). We define $D_i = RSS_i - RSS_0$. Thus, when $d_i = \varphi$, $D_i = 0$.

Let samples of D_i be taken at equally spaced time intervals of T seconds. Let $S(N)$ denote all the information available for decision making at the $N\mathrm{th}$ sampling instant as

$$S(N) = \{(D_i(N), D_i(N-1)\ldots, D_i(N-P+1), M_i)_{i=1\ldots Q}, H, \phi(N-1)\}. \tag{1}$$

In (1), $D_i(N), D_i(N-1), \ldots D_i(N-P+1)$ is the sequence of the latest P samples of D_i, $D_i(N)$ is the latest sample of D_i, and M_i is the sampling instant when the MH passed the position of $d_i = \varphi$ last time.

Based on the definition of M_i, we can obtain the following:

$$\begin{aligned}&(\forall j \in M_i \ldots N-2)((D_i(j) \cdot D_i(N-1) > 0) \wedge \\ &(D_i(M_i - 1) \cdot D_i(N-1) < 0)).\end{aligned} \tag{2}$$

Also, in (1), H is the sampling instant of last handoff, and $\phi(N)$ is the network selection at sampling instant N, which is a function of $S(N)$:

$$\phi(N) = \xi(S(N)) = \begin{cases} i, & 1 \le i \le Q, \text{ choose } WLAN_i, \\ -1, & \text{choose 3G.} \end{cases} \tag{3}$$

Thus, $\phi(N-1)$ in (1) is the network selection at sampling instant $N-1$.

Note that (1) is only used for the algorithm expression. In an actual application, the MH only has to record the information of those WLANs whose signals can be detected instead of recording information from all Q WLANs.

Based on the above definitions, we can reach the conclusion that if $\phi(X) \ne \phi(Y)$ $(X < Y)$, network selections at sampling instants X and Y are different, which means that there is at least one handoff between X and Y. Specifically, when $\phi(X) \cdot \phi(Y) > 0$ and $Y = X + 1$, it means that there is an HHO at sampling instant Y, whereas $\phi(X) \cdot \phi(Y) < 0$ and $Y = X + 1$ means that there is a VHO at sampling instant Y.

Based on $\phi(N)$, we can get the following expression for H:

$$(\forall j \in H \ldots N-2)((\phi(j) = \phi(N-1)) \wedge (\phi(H-1) \neq \phi(N-1))). \tag{4}$$

In addition, assume that at sampling instant N, $WLAN_{maxD(N)}$ has the strongest RSS. Thus, we can get

$$D_{maxD(N)}(N) = MAX(D_1(N), D_2(N) \ldots, D_Q(N)). \tag{5}$$

We define

$$\begin{aligned} D_{-1}(N) &= -D_{maxD(N)}(N) \\ &= -MAX(D_1(N), D_2(N) \ldots, D_Q(N)). \end{aligned} \tag{6}$$

We also introduce $ST_i(N)$ to indicate the dwelling information of MH in $WLAN_i$ at sampling instant N:

$$ST_i(N) = \mathrm{sgn}(D_i(N))(N - M_i)T \; (i = 1 \ldots Q). \tag{7}$$

The sgn function is defined as

$$\mathrm{sgn}(x) = \begin{cases} 0, & x = 0, \\ x/|x|, & others. \end{cases} \tag{8}$$

In order to handle the case that $D_i(N) = 0$ in (7), we will set $D_i(N) = D_i(N-1)$ until we get a nonzero value.

If $ST_i(N) > 0$, it means that at sampling instant N, the MH has stayed in the area of $WLAN_i$ where $RSS_i > RSS_0$ for a period of $ST_i(N)$, whereas $ST_i(N) < 0$ means that at sampling instant N, the MH has stayed in the area of $WLAN_i$ where $RSS_i < RSS_0$ for a period of $-ST_i(N)$. We also get the following:

$$ST_{maxST(N)}(N) = MAX(ST_1(N), ST_2(N) \ldots, ST_Q(N)), \tag{9}$$

$$\begin{aligned} ST_{-1}(N) &= -ST_{maxST(N)}(N) \\ &= -MAX(ST_1(N), ST_2(N) \ldots, ST_Q(N)). \end{aligned} \tag{10}$$

6 Enhancement of Existing Handoff Algorithms and Their Performance Analysis

The hysteresis-based algorithm (HY) is a traditional HHO algorithm that is widely used in radio cellular systems. However, because RSSs measured from different networks display a significant variety due to different techniques in the physical layers and cannot be compared with each other, HY cannot be applied to VHO directly. In this paper, we extend the traditional HY to support both VHO and HHO decisions and apply it to complex heterogeneous wireless environments. We name the enhanced algorithm as E-HY.

Based on the definition of $\phi(N)$, the handoff policy of E-HY can be described by the following (h_y denotes hysteresis):

$$\phi(N-1) \neq \phi(N) \leftrightarrow D_{\phi(N-1)}(N) < -h_y. \tag{11}$$

The relevant deductions for obtaining the above expression are provided in Appendix A.

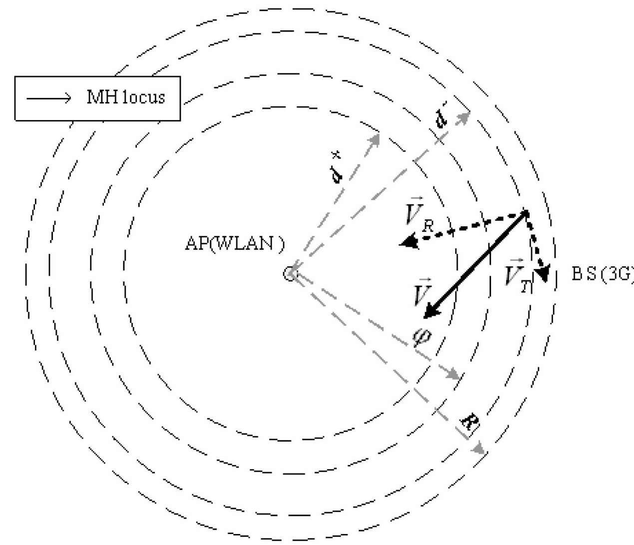


Fig. 2. Traversing scenario for performance analysis.

Thus, we can get the definition of $\phi(N)$ in E-HY as

$$\phi(N) = \begin{cases} \phi(N-1), & D_{\phi(N-1)}(N) \geq -h_y, \\ maxD(N), & (D_{\phi(N-1)}(N) < -h_y) \wedge (-D_{-1}(N) > h_y), \\ -1, & others. \end{cases} \tag{12}$$

In addition, we can extend the traditional dwelling timer-based algorithm to support both VHO and HHO decisions and get the handoff policy of E-DW (t_{dw} denotes the dwelling timer) as

$$\phi(N-1) \neq \phi(N) \leftrightarrow ST_{\phi(N-1)}(N) < -t_{dw}. \tag{13}$$

The relevant deductions for obtaining the above expression are provided in Appendix B.

The definition of $\phi(N)$ in E-DW can be described as

$$\phi(N) = \begin{cases} \phi(N-1), & ST_{\phi(N-1)}(N) \geq -t_{dw}, \\ maxST(N), & (ST_{\phi(N-1)}(N) < -t_{dw}) \wedge (-ST_{-1}(N) > t_{dw}), \\ -1, & others. \end{cases} \tag{14}$$

Next, we will analyze the performance of E-HY and E-DW during the process of an MH traversing one WLAN. Consider the movement scenario as shown in Fig. 2, where the coverage area of the WLAN is a circle whose center is its AP. The MH's velocity vector is $\vec{V} = \vec{V}_R + \vec{V}_T$, where $\vec{V}_R$ is the radial component and $\vec{V}_T$ is the tangential component. $\vec{V}_T$ has no effect on signal strength and handoff trigger. Thus, in the following analysis, unless specified otherwise, the velocity of the MH refers only to $\vec{V}_R$.

Assume that the radius of the coverage area of the WLAN is R. The coordinates of the AP are (0, 0). When the distance from the MH to the AP is $d = d^+$, $D = RSS - RSS_0 = h_y$, and when $d = d^-$, $D = -h_y$. The MH takes one point at the circle of $d = R$ as the origin and moves toward the AP by a uniform rectilinear motion with fixed speed v until it reaches another point at the circle of $d = R$. Assume that the initial network access of the MH is a 3G network. During the movement of the MH, the sampling instants of handoff in E-HY and E-DW can be described as follows:

E-HY

$$\text{Enter WLAN}: N'_{HY} = \frac{R - d^+}{v \cdot T}, \tag{15}$$

$$\text{Exit WLAN}: N''_{HY} = \frac{R + d^-}{v \cdot T}. \tag{16}$$

E-DW

$$\text{Enter WLAN}: N'_{DW} = \frac{R - \varphi}{v \cdot T} + \frac{t_{dw}}{T}, \tag{17}$$

$$\text{Exit WLAN}: N''_{DW} = \frac{R + \varphi}{v \cdot T} + \frac{t_{dw}}{T}. \tag{18}$$

During the movement of the MH, the MR of E-HY and E-DW can be calculated as

$$MR_{HY} = 1 - \frac{d^- - d^+}{2R}, \tag{19}$$

$$MR_{DW} = \begin{cases} 1 - \frac{v \cdot t_{dw}}{R,} & v \le \frac{R-\varphi}{t_{dw}}, \\ \frac{1}{2} - \frac{v \cdot t_{dw} - \varphi}{2R,} & \frac{R-\varphi}{t_{dw}} < v \le \frac{2\varphi}{t_{dw}}, \\ 1 - \frac{\varphi}{R}, & v > \frac{2\varphi}{t_{dw}}. \end{cases} \tag{20}$$

From (19) and (20), we can see that the MR of E-HY has no relation to v. In contrast, the MR of E-DW will reduce linearly as v increases until reaching its lower limit.

Assume that when $v = v_{HO}$, E-HY and E-DW trigger handoff at the same sampling instant. Thus, we can get

$$v_{HO} = \frac{d^- - d^+}{2t_{dw}}. \tag{21}$$

From (19)-(21), we can obtain the following conclusions:

- When $v > v_{HO}$, MR_{HY} stays unchanged and MR_{DW} reduces; thus, we have $MR_{HY} > MR_{DW}$.
- When $v < v_{HO}$, MR_{HY} stays unchanged and MR_{DW} increases; thus, we have $MR_{HY} < MR_{DW}$.

When MH exits the WLAN, in response to the handoff policy and the environment condition, it will either execute HHO (switch to another WLAN) or VHO (switch to the 3G network). Specifically, we can find the distance between different APs δ, which will guarantee that the MH will switch from one WLAN to another WLAN, and no VHO will be triggered as

$$\text{E-HY}: \delta_{HY} \le d^+ + d^-, \tag{22}$$

$$\text{E-DW}: \delta_{DW} \le 2\varphi. \tag{23}$$

7 A Novel General Handoff Algorithm and Its Performance Analysis

According to the analysis in the previous section, we can see that a simple method to improve the MR is to use the E-HY algorithm when $v > v_{HO}$ and use the E-DW algorithm when $v < v_{HO}$. However, it is difficult to obtain the velocity of the MH, especially $\vec{V}_R$. In a practical environment, we must get the position coordinates of the MH and periodically determine their changes to calculate the velocity of the MH. Constantly monitoring the MH's accurate position is expensive, power consuming, and subject to the influence of the environment.

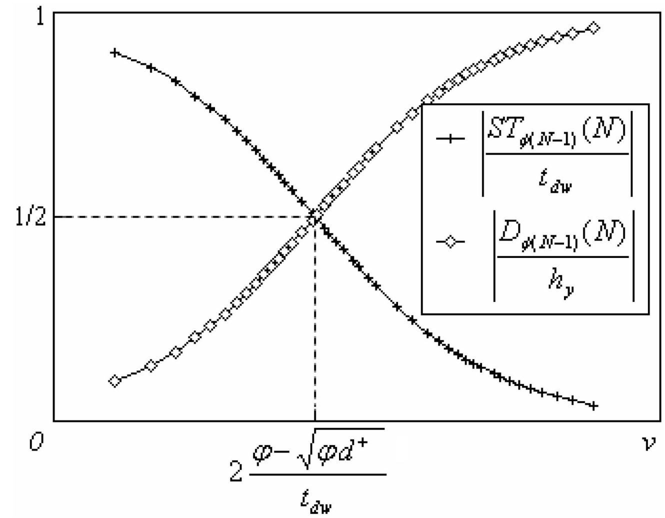


Fig. 3. Analysis of influence factors in the handoff policy of GHO.

In order to improve the MR, let us examine the handoff conditions of E-HY and E-DW again. Equations (11) and (13) can be expressed as follows:

E-HY:

$$\phi(N-1) \ne \phi(N) \leftrightarrow \frac{D_{\phi(N-1)}(N)}{h_y} < -1. \tag{24}$$

E-DW:

$$\phi(N-1) \ne \phi(N) \leftrightarrow \frac{ST_{\phi(N-1)}(N)}{t_{dw}} < -1. \tag{25}$$

Thus, we can design a novel general handoff algorithm GHO for heterogeneous wireless networks whose handoff policy can be described by the following:

$$\phi(N-1) \ne \phi(N) \leftrightarrow \alpha \frac{D_{\phi(N-1)}(N)}{h_y} + \beta \frac{ST_{\phi(N-1)}(N)}{t_{dw}} < -1. \tag{26}$$

In the following analysis and implementation, we set the weight values in (26) as $\alpha = \beta = 1$. Setting different weight values according to the MH's status (for example, moving speed), user preferences, or other environmental factors may improve the handoff performance. However, it will add measurement and computational costs. We will explore the optimal weight values for these parameters and how we can determine them in different scenarios in our future work.

Fig. 3 shows the change in the influence factors in (26) with different values of v. In Fig. 3, the x-axis adopts the logarithmic scale in order to show the instance when v is very large.

In Fig. 3, we record the values of $\left|\frac{D_{\phi(N-1)}(N)}{h_y}\right|$ and $\left|\frac{ST_{\phi(N-1)}(N)}{t_{dw}}\right|$, respectively, when handoff is triggered in GHO. As shown in Fig. 3, when $v < 2\frac{\varphi - \sqrt{\varphi d^+}}{t_{dw}}$, $\left|\frac{D_{\phi(N-1)}(N)}{h_y}\right| < \left|\frac{ST_{\phi(N-1)}(N)}{t_{dw}}\right|$; thus, $\frac{ST_{\phi(N-1)}(N)}{t_{dw}}$ will be more dominating in the handoff policy of GHO, which means that GHO will be more similar to E-DW.

When $v > 2\frac{\varphi - \sqrt{\varphi d^+}}{t_{dw}}$, $\left|\frac{D_{\phi(N-1)}(N)}{h_y}\right| > \left|\frac{ST_{\phi(N-1)}(N)}{t_{dw}}\right|$; thus, $\frac{D_{\phi(N-1)}(N)}{h_y}$ will be more dominating in the handoff policy of GHO, which means that GHO will be more similar to E-HY.

The $\phi(N)$ in GHO can be defined as

$$\phi(N) = \begin{cases} maxGHO, & MAX\left(\left(\frac{D_i(N)}{h_y} + \frac{ST_i(N)}{t_{dw}}\right)_{i=1\ldots Q}\right) \geq 1 \\ & \wedge \frac{D_{\phi(N-1)}(N)}{h_y} + \frac{ST_{\phi(N-1)}(N)}{t_{dw}} < -1, \\ -1, & MAX\left(\left(\frac{D_i(N)}{h_y} + \frac{ST_i(N)}{t_{dw}}\right)_{i=1\ldots Q}\right) < 1 \\ & \wedge \frac{D_{\phi(N-1)}(N)}{h_y} + \frac{ST_{\phi(N-1)}(N)}{t_{dw}} < -1, \\ \phi(N-1), & others. \end{cases} \tag{27}$$

In (27), *maxGHO* satisfies the following:

$$\frac{D_{maxGHO}(N)}{h_y} + \frac{ST_{maxGHO}(N)}{t_{dw}} = MAX\left(\left(\frac{D_i(N)}{h_y} + \frac{ST_i(N)}{t_{dw}}\right)_{i=1\ldots Q}\right).$$

We can analyze the performance of GHO in the same scenario as mentioned in the last section. Assume that, during the movement of the MH, the sampling instants of handoff in GHO are N'_{GHO} (entering the WLAN) and N''_{GHO} (exiting the WLAN). At N'_{GHO}, the distance from the MH to the AP is $d = d_1$. At N''_{GHO}, the distance from the MH to the AP is $d = d_2$.

Thus,

$$MR_{GHO} = 1 - \frac{d_2 - d_1}{2R}. \tag{28}$$

When the distance from the MH to the AP is d, the RSS from the WLAN can be expressed as follows:

$$RSS(d) = K_1 - K_2 \log(d) + \Omega(d). \tag{29}$$

K_1 represents the gain of the transmission, the reception antennas, and the wavelength-dependent part of the channel model, whereas K_2 represents environment-specific attenuation characteristics. $\Omega(d)$ represents the zero-mean Gaussian process.

Ignoring $\Omega(d)$, when $d = \varphi$, we can get

$$RSS_0 = K_1 - K_2 \log(\varphi). \tag{30}$$

Thus, when $d = d^+$, we can get

$$K_2 \log(\varphi / d^+) = h_y. \tag{31}$$

When $d = d^-$,

$$K_2 \log(d^- / \varphi) = h_y. \tag{32}$$

Thus, it can be concluded from (31) and (32) that $d^+ d^- = \varphi^2$.

Then, based on (30) and (31), we can get

$$\begin{cases} K_2 = \frac{h_y}{\log(\varphi/d^+)}, \\ K_1 - RSS_0 = \frac{h_y \cdot \log(\varphi)}{\log(\varphi/d^+)}. \end{cases} \tag{33}$$

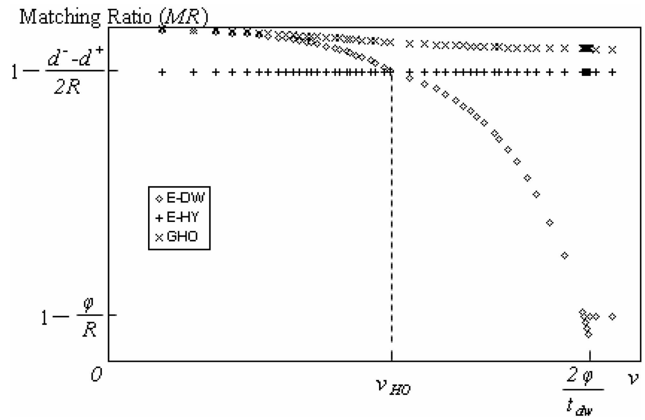


Fig. 4. *MR* of E-HY, E-DW, and GHO as v changes.

Thus,

$$D(N) = \frac{h_y \cdot \log(\varphi)}{\log(\varphi/d^+)} - \frac{h_y}{\log(\varphi/d^+)} \log(d). \tag{34}$$

According to (27), at N'_{GHO}, we can get

$$-\frac{D(N'_{GNO})}{h_y} - \frac{ST(N'_{GHO})}{t_{dw}} = -1. \tag{35}$$

At N''_{GHO}, we can get

$$\frac{D(N''_{GNO})}{h_y} + \frac{ST(N''_{GHO})}{t_{dw}} = -1. \tag{36}$$

Based on (7), (34), (35), and (36), we can get

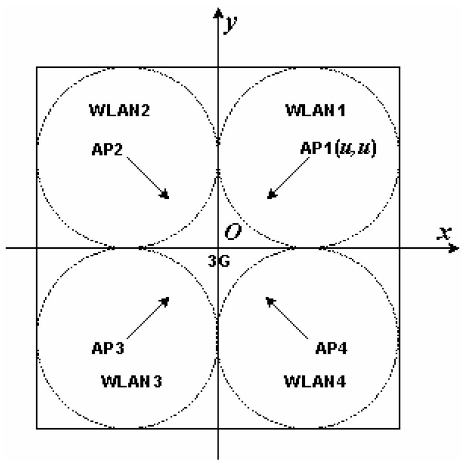
$$\begin{cases} \frac{\log(\varphi/d_1)}{\log(\varphi/d^+)} + \frac{\varphi - d_1}{v \cdot t_{dw}} = 1, \\ \frac{\log(\varphi/d_2)}{\log(\varphi/d^+)} + \frac{\varphi - d_2}{v \cdot t_{dw}} = -1. \end{cases} \tag{37}$$

Based on (28) and (37), we can get the numerical solution of MR_{GHO}. Compared with E-HY and E-DW, GHO can achieve better MR, as shown in Fig. 4. In Fig. 4, the x-axis adopts the logarithmic scale in order to show the instance when v is very large. In addition, the related computing requirement of GHO is very simple to be suitable for mobile devices with limited computing capacity.

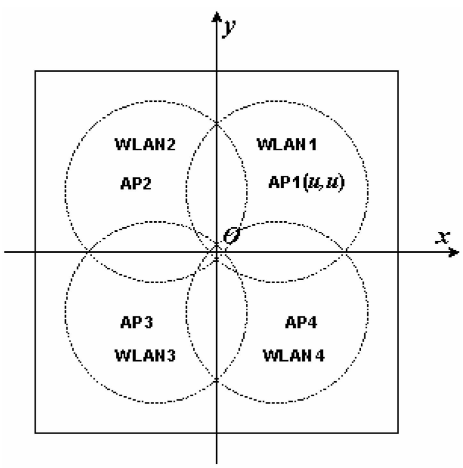
8 Performance Evaluation

8.1 Simulation Scenario

We design and implement a simulation model, as shown in Fig. 5, to act as a benchmark for the performance evaluation of the VHO algorithms. Assume that MH takes a random rectilinear motion without pause in the square containing four APs, as shown in Fig. 5. The side length of the square is $a = 600$ m. This square is completely covered by a 3G network. The coverage area of each AP is a circle whose radius is $R = 150$ m. The position coordinates of the four APs are (u, u), $(-u, u)$, $(-u, -u)$, and $(u, -u)$. By setting u as different values, this model can simulate different handoff scenarios. When $u = 150$ m, as shown in Fig. 5a, there is no overlapping between the coverage areas of the different APs. When $u = 100$ m, as shown in Fig. 5b, there is a significant overlap between the coverage areas of the different APs.



(a)



(b)

Fig. 5. Simulation model illustration. (a) $u = 150\ \mathrm{m}$. (b) $u = 100\ \mathrm{m}$.

In our simulations, we respectively set $u = 150\ \mathrm{m}, 145\ \mathrm{m}, 140\ \mathrm{m}, \ldots, 100\ \mathrm{m}$. Random rectilinear motion means that the MH randomly chooses the destination in the square area, moves straight to the destination with constant speed v, and then repeats the procedure. Choosing a destination and changing the direction will not consume time. Destination selection satisfies a uniform distribution in the square area. In order to get rid of random causes, each simulation includes more than 10,000 continuous random rectilinear motion procedures.

In order to evaluate the performance of the algorithms under different moving speeds of the MH, for each value of u, we respectively set v as 1, 2, 5, 10, and 20 m/s when performing the simulations. We can consider 1 and 2 m/s as the speed of pedestrians, whereas 5, 10, and 20 m/s reflect the speed of different vehicles in the city.

In addition, we set d^+, φ, and d^- as 120, 129.6, and 140 m, respectively. The sampling interval $T = 0.05\ \mathrm{s}$ and t_{dw} in E-DW is 5 s.

In our simulations, we assume that the WLANs are based on the IEEE 802.11b Standard supporting the rate of 11 megabits per second (Mbps), whereas 3G networks are based on the CDMA 2000 Standard supporting the rate of 384 kilobits per second (Kbps) for pedestrian velocity $(v <= 2m/s)$ and the rate of 144 Kbps for vehicular velocity $(v > 2m/s)$.

TABLE 1
Simulation Parameters

PARAMETER	VALUE
HHO latency	2s
VHO latency	2s
Packet size	1500Bytes
TCP protocol	Reno
RTT of TCP traffic	1s
UDP traffic type	CBR
Sending rate of CBR	2Mbps

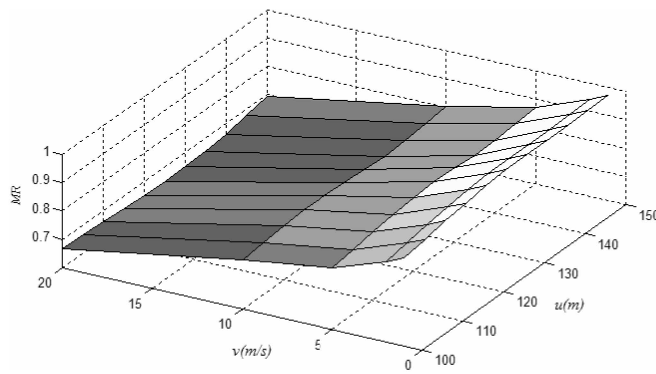


Fig. 6. Change trend of *MR* to the values of v and u in E-DW.

We use the *MR*, TCP throughput, and UDP throughput as the evaluation criteria and compare the performance of GHO against E-HY and E-DW. For TCP throughput comparison, we simulate the MH download data from a fixed ftp server, whereas, for UDP throughput comparison, we simulate the MH receiving constant UDP traffic from a fixed node. In order to eliminate the influence of other traffic, we assume that there is no other cross traffic in our simulations. Other simulation parameters are shown in Table 1.

8.2 Simulation Results

Figs. 6, 7, and 8 show the relationship between *MR*, $v(\mathrm{m/s})$, and $u(\mathrm{m})$ in E-DW, E-HY, and GHO. We can see that as v increases, the *MR* of E-DW will decrease, whereas, as u increases, its *MR* increases. In contrast, v has little influence on *MR* in E-HY. When u increases, E-HY's *MR* will increase, but the change range is small (between 86.8 percent and 92.1 percent). For GHO, when v is slow, the change trend of its *MR* is similar to E-DW, whereas, when v is fast, the change trend of its *MR* is similar to E-HY.

When v is slow, the *MR* of E-DW is about 5 percent higher than E-HY, whereas, when v is fast, E-HY can get about 20 percent higher *MR* than E-DW. No matter what the value of v is, GHO can get better *MR* than E-DW and E-HY. This conclusion is consistent with the analytical results in the previous sections.

Figs. 9, 10, 11, 12, 13, and 14 show the relationship between throughput, $v(\mathrm{m/s})$, and $u(\mathrm{m})$ in E-DW, E-HY, and GHO. As v increases, the TCP and UDP throughput of all these algorithms will obviously decrease. This is especially so for the TCP throughput. However, GHO achieves better throughput for both TCP and UDP compared with E-DW and E-HY.

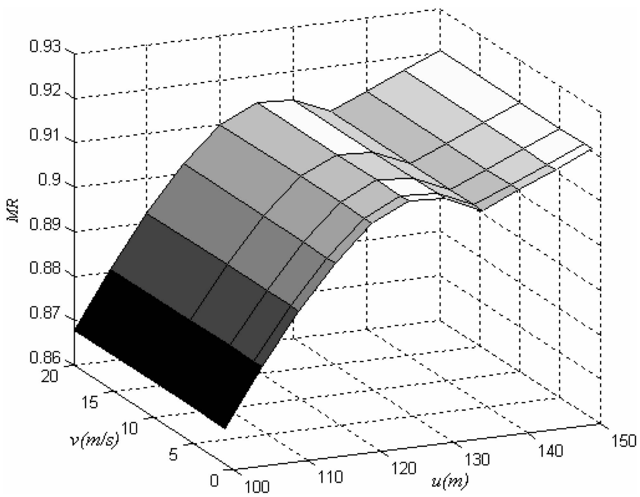


Fig. 7. Change trend of *MR* to the values of v and u in E-HY.

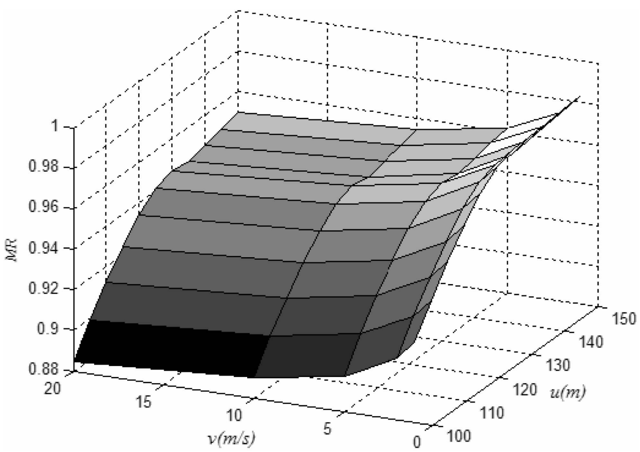


Fig. 8. Change trend of *MR* to the values of v and u in GHO.

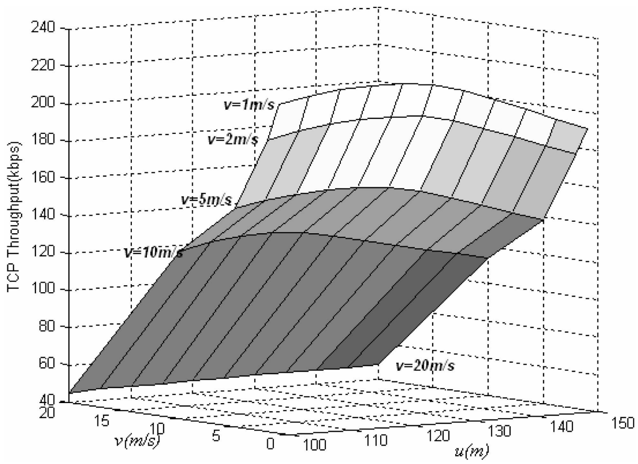


Fig. 9. Change trend of TCP throughput to the values of v and u in E-DW.

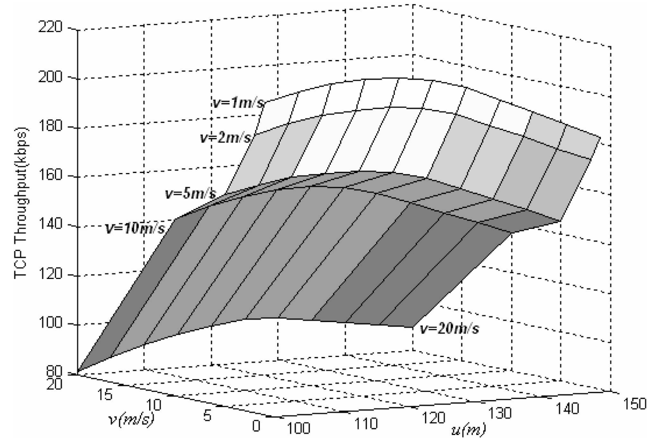


Fig. 10. Change trend of TCP throughput to the values of v and u in E-HY.

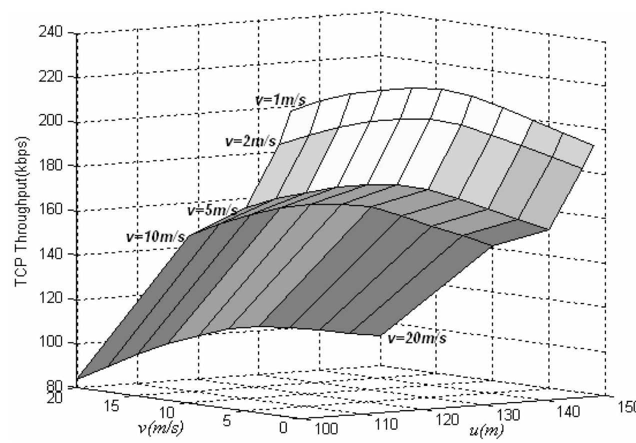


Fig. 11. Change trend of TCP throughput to the values of v and u in GHO.

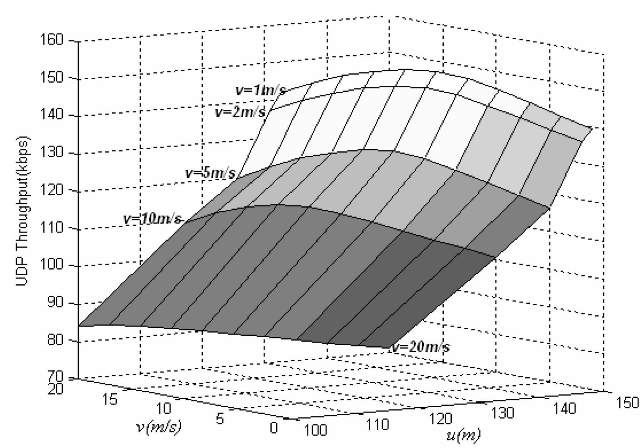


Fig. 12. Change trend of UDP throughput to the values of v and u in E-DW.

Tables 2 and 3 show the performance comparison between E-DW, E-HY, and GHO under low moving speed $v = 1\ \mathrm{m/s}$ and high moving speed $v = 20\ \mathrm{m/s}$ with different values of u. In Table 2, $u = 150\ \mathrm{m}$ (the largest value of u in our simulations), and we have a pure VHO scenario. In Table 3, $u = 100\ \mathrm{m}$ (the smallest value of u in our simulations), and we have a mixed scenario of VHO and HHO. Based on Tables 2 and 3, we can make a quantitative comparison of the performance of these algorithms.

In the pure VHO scenario, as shown in Table 2, for *MR*, under low moving speed, GHO is 1 percent higher than E-DW and 6 percent higher than E-HY, whereas, under high moving speed, GHO is 25.7 percent higher than E-DW and 3 percent higher than E-HY. For the TCP throughput, under low moving speed, GHO is 1 percent higher than E-DW and 6 percent higher than E-HY, whereas, under high moving speed, GHO is 85.4 percent higher than E-DW and 5.6 percent higher than E-HY. For the UDP throughput, under low moving speed, GHO is

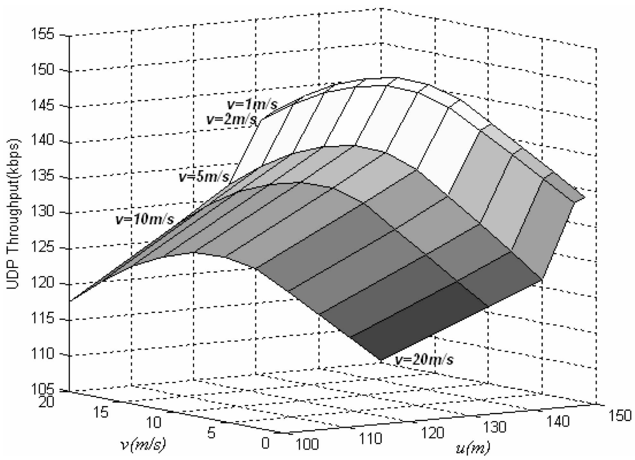


Fig. 13. Change trend of UDP throughput to the values of v and u in E-HY.

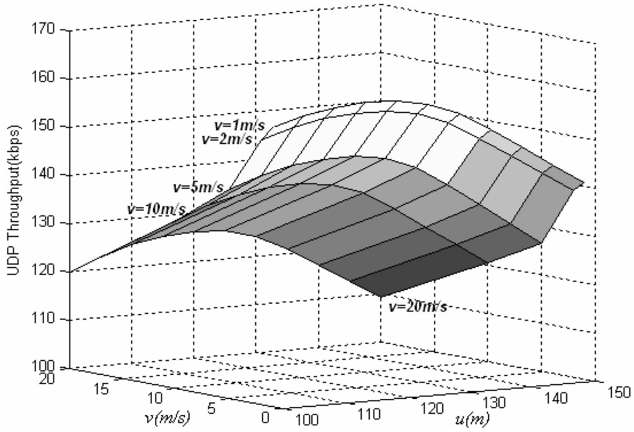


Fig. 14. Change trend of UDP throughput to the values of v and u in GHO.

0.7 percent higher than E-DW and 5.2 percent higher than E-HY, whereas, under high moving speed, GHO is 47.9 percent higher than E-DW and 3.8 percent higher than E-HY.

In the mixed VHO and HHO scenario, as shown in Table 3, for *MR*, under low moving speed, GHO is 1 percent higher than E-DW and 5.2 percent higher than E-HY, whereas, under high moving speed, GHO is 20.1 percent higher than E-DW and 1.7 percent higher than E-HY. For the TCP throughput, under low moving speed, GHO is 5.3 percent higher than E-DW and 5.3 percent higher than E-HY, whereas, under high moving speed, GHO is 82.2 percent higher than E-DW and 2.4 percent higher than E-HY. For the UDP throughput, under low moving speed, GHO is 1.3 percent higher than E-DW and 5.3 percent higher than E-HY, whereas under high moving speed, GHO is 40.5 percent higher than E-DW and 1.7 percent higher than E-HY.

Fig. 15 shows a comparison between GHO and another VHO decision algorithm PreRSS-Cost [13]. Considering that the PreRSS-Cost algorithm also supports both VHO and HHO, we set $u = 100$ m and evaluated the TCP and UDP throughput of these two algorithms under different moving speeds of the MH ($v = 1$, 2, 5, 10, and 20 m/s, respectively). As shown in Fig. 15, as v increases, the TCP and UDP throughput of these two algorithms will both decrease. However, GHO achieves better throughput for both TCP and UDP compared with PreRSS-Cost. Under low moving speed, GHO will get about 5 percent higher throughput, whereas, under high moving speed, GHO will get about 3 percent higher throughput.

TABLE 2
Comparison between E-DW, E-HY, and GHO, with $u = 150$ m

	Algorithm	v=1m/s	v=20m/s
MR	E-DW	97.2%	69.3%
	E-HY	92.1%	92.1%
	GHO	98.2%	95.0%
TCP throughput	E-DW	191kbps	48kbps
	E-HY	182kbps	89kbps
	GHO	193kbps	94kbps
UDP throughput	E-DW	140kbps	71kbps
	E-HY	134kbps	105kbps
	GHO	141kbps	109kbps

TABLE 3
Comparison between E-DW, E-HY, and GHO, with $u = 100$ m

	Algorithm	v=1m/s	v=20m/s
MR	E-DW	91.0%	66.7%
	E-HY	86.8%	86.8%
	GHO	92.0%	88.5%
TCP throughput	E-DW	207kbps	45kbps
	E-HY	207kbps	82kbps
	GHO	218kbps	84kbps
UDP throughput	E-DW	156kbps	84kbps
	E-HY	150kbps	118kbps
	GHO	158kbps	120kbps

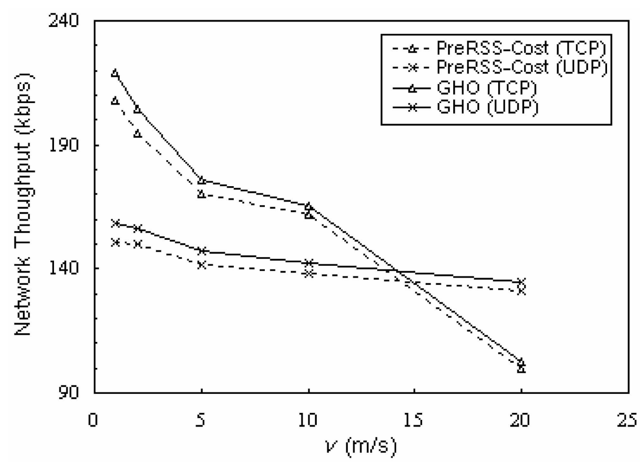


Fig. 15. Comparison of TCP and UDP throughput between GHO and PreRSS-Cost under different values of v.

9 Conclusion and Future Work

In this paper, we first presented an analytical framework to evaluate VHO algorithms. This framework can be used to provide guidelines for the optimization of handoff in heterogeneous wireless networks. Subsequently, we extended the traditional hysteresis-based and dwelling-timer-based algorithms to support both VHO and HHO decisions. We referred to these algorithms as E-HY and E-DW, respectively. Based on the proposed analytical model, we provided a formalization definition of handoff conditions in E-HY and E-DW and analyzed their performance. Analysis showed that the *MR* of E-HY has no relation with the MH's moving speed. In contrast, the *MR* of E-DW will reduce linearly as the MH's moving speed increases until reaching a lower limit. As a result, when the moving speed is slow, E-DW will get better performance, whereas, when the moving speed is high, E-HY will perform better. Based on the analysis, we proposed a novel handoff decision algorithm GHO to trigger HHO and VHO at appropriate times in heterogeneous wireless networks. GHO synthetically considers the handoff policy of E-DW and E-HY. In addition, when the moving speed is slow, the handoff condition in GHO will be more similar to E-DW, and when the moving speed is high, its handoff condition will be more similar to E-HY. Analysis and simulations show that GHO can achieve better performance than E-DW, E-HY, and PreRSS-Cost.

In our future work, we will explore the optimal weight values of the influence factors in (26) and how we can determine them in different scenarios. In addition, we will investigate bandwidth-aware VHO techniques, which consider the residual bandwidth of WLANs as one criterion for handoff decisions without relying on special network support such as the QBSS load.

Appendix A

Based on the handoff policy of HY, we make the following assumptions for the handoff conditions of E-HY:

1. Assume that an MH is in the 3G network. When the MH senses a $WLAN_i$ with $RSS_i > RSS_0 + h_y$, the MH will switch from the 3G network to $WLAN_i$.
2. Assume that an MH is in $WLAN_i$. When $RSS_i < RSS_0 - h_y$, the MH will switch from $WLAN_i$ to $WLAN_j$ (if the MH can sense another $WLAN_j$ with $RSS_j > RSS_0 + h_y$) or from $WLAN_i$ to 3G (if the MH cannot sense another $WLAN_j$ with $RSS_j > RSS_0 + h_y$).

Thus, we can get the following for the handoff policy of E-HY:

$$\begin{aligned}&\phi(N-1) \neq \phi(N) \leftrightarrow \\ &(\phi(N-1) < 0 \wedge (\exists i(D_i(N) > h_y))) \\ &\vee (\phi(N-1) > 0 \wedge D_{\phi(N-1)}(N) < -h_y).\end{aligned} \tag{A.1}$$

$$\begin{aligned}&\exists i(D_i(N) > h_y) \leftrightarrow MAX(D_i(N))_{i=1 \ldots Q} > h_y \leftrightarrow \\ &- MAX(D_i(N))_{i=1 \ldots Q} < -h_y.\end{aligned}$$

Based on (6), we can get $-MAX(D_i(N))_{i=1..Q} = D_{-1}(N)$.

Thus, (A.1) can be expressed as

$$\begin{aligned}\phi(N-1) \neq \phi(N) \leftrightarrow &(\phi(N-1) < 0 \wedge D_{-1}(N) < -h_y) \\ &\vee (\phi(N-1) > 0 \wedge D_{\phi(N-1)}(N) < -h_y).\end{aligned} \tag{A.2}$$

Considering the actual range of $\phi(N-1)$, when $\phi(N-1) < 0$, $\phi(N-1) = -1$. Thus, (A.2) can be simplified to

$$\phi(N-1) \neq \phi(N) \leftrightarrow D_{\phi(N-1)}(N) < -h_y. \tag{11}$$

Appendix B

Based on the handoff policy of the dwelling timer, we make the following assumptions for the handoff conditions of E-DW:

1. Assume that an MH is in the 3G network. When the dwelling time of the MH in the area of $WLAN_i$ with $RSS_i > RSS_0$ exceeds t_{dw}, the MH will switch from the 3G network to $WLAN_i$.
2. Assume that an MH is in $WLAN_i$. When the dwelling time of the MH in the area of $WLAN_i$ with $RSS_i < RSS_0$ exceeds t_{dw}, the MH will switch from $WLAN_i$ to $WLAN_j$ (if the MH has sensed another $WLAN_j$ with $RSS_j > RSS_0$ for a time longer than t_{dw}) or from $WLAN_i$ to the 3G network (if the MH has not sensed another $WLAN_j$ with $RSS_j > RSS_0$ for a time longer than t_{dw}).

Thus, we can get the following expression of the handoff policy of E-DW:

$$\begin{aligned}&\phi(N-1) \neq \phi(N) \leftrightarrow \\ &(\phi(N-1) < 0 \wedge (\exists i(D_i(N) > 0 \wedge (N - M_i)T > t_{dw}))) \vee \\ &(\phi(N-1) > 0 \wedge D_{\phi(N-1)}(N) < 0 \wedge (N - M_{\phi(N-1)})T > t_{dw}).\end{aligned} \tag{B.1}$$

Based on (7), we can get

$$\begin{aligned}&D_{\phi(N-1)}(N) < 0 \wedge (N - M_{\phi(N-1)})T > t_{dw} \leftrightarrow \\ &\mathrm{sgn}(D_{\phi(N-1)}(N)) = -1 \wedge (N - M_{\phi(N-1)})T > t_{dw} \leftrightarrow \\ &ST_{\phi(N-1)}(N) < -t_{dw}.\end{aligned}$$

Thus, (B.1) can be expressed as

$$\begin{aligned}&\phi(N-1) \neq \phi(N) \leftrightarrow \\ &(\phi(N-1) < 0 \wedge (\exists i(D_i(N) > 0 \wedge (N - M_i)T > t_{dw}))) \\ &\vee (\phi(N-1) > 0 \wedge ST_{\phi(N-1)}(N) < -t_{dw}).\end{aligned} \tag{B.2}$$

Based on the definition of M_i, $N > M_i$. Thus, we can get

$$\begin{aligned}&\exists i(D_i(N) > 0 \wedge (N - M_i)T > t_{dw}) \leftrightarrow \\ &\exists i(\mathrm{sgn}(D_i(N))(N - M_i)T > t_{dw}) \leftrightarrow \\ &MAX(\mathrm{sgn}(D_i(N))(N - M_i)T)_{i=1 \ldots Q} > t_{dw}.\end{aligned}$$

Based on (7), we can get

$$\exists i(D_i(N) > 0 \wedge (N - M_i)T > t_{dw}) \leftrightarrow MAX(ST_i(N))_{i=1 \ldots Q} > t_{dw}.$$

Based on (10), we can get

$$\begin{aligned}&\exists i(D_i(N) > 0 \wedge (N - M_i)T > t_{dw}) \leftrightarrow \\ &MAX(ST_i(N))_{i=1 \ldots Q} > t_{dw} \leftrightarrow \\ &ST_{-1}(N) < -t_{dw}.\end{aligned}$$

Thus, (B.2) can be expressed as

$$\begin{aligned}&\phi(N-1) \neq \phi(N) \leftrightarrow \\ &(\phi(N-1) < 0 \wedge ST_{-1}(N) < -t_{dw}) \\ &\vee (\phi(N-1) > 0 \wedge ST\phi(N-1)(N) < -t_{dw}).\end{aligned} \tag{B.3}$$

Considering the actual range of $\phi(N-1)$, when $\phi(N-1) < 0$, $\phi(N-1) = -1$. Thus, (B.3) can be simplified to

$$\phi(N-1) \neq \phi(N) \leftrightarrow ST_{\phi(N-1)}(N) < -t_{dw}. \tag{13}$$

ACKNOWLEDGMENTS

This work was supported by the National Basic Research Program of China (No. 2007CB310702) and the National Natural Science Foundation of China (No. 90604016).

REFERENCES

[1] A.H. Zahran, B. Liang, and A. Saleh, "Signal Threshold Adaptation for Vertical Handoff in Heterogeneous Wireless Networks," *Mobile Networks and Applications,* pp. 625-640, 2006.

[2] K. Pahlavan, P. Krishnamurthy, and A. Hatami, "Handoff in Hybrid Mobile Data Networks," *IEEE Personal Comm.,* vol. 7, no. 2, pp. 34-47, Apr. 2000.

[3] J. Hou and D.C. O'Brien, "Vertical Handover-Decision-Making Algorithm Using Fuzzy Logic for the Integrated Radio-and-OW System," *IEEE Trans. Wireless Comm.,* vol. 5, no. 1, pp. 176-185, Jan. 2006.

[4] N. Zhang and J.M. Holtzman, "Analysis of Handoff Algorithms Using Both Absolute and Relative Measurements," *IEEE Trans. Vehicular Technology,* vol. 45, no. 1, pp. 174-179, Feb. 1996.

[5] P. Marichamy, S. Chakrabarti, and S.L. Maskara, "Performance Evaluation of Handoff Detection Schemes," *Proc. IEEE Region 10 Conf. Convergent Technologies for the Asia-Pacific (TENCON '03),* vol. 2, pp. 643-646, Oct. 2003.

[6] A. Hatami, P. Krishnamurthy, K. Pahlavan, M. Ylianttila, J. Makela, and R. Pichna, "Analytical Framework for Handoff in Non-Homogeneous Mobile Data Networks," *Proc. 10th IEEE Int'l Symp. Personal, Indoor and Mobile Radio Comm. (PIMRC '99),* pp. 760-764, Sept. 1999.

[7] M. Ylianttila, M. Pande, J. Makela, and P. Mahonen, "Optimization Scheme for Mobile User Performing Vertical Handoffs between IEEE 802.11 and GPRS/EDGE Networks," *Proc. IEEE Global Telecomm. Conf. (GLOBECOM '01),* pp. 3439-3443, Nov. 2001.

[8] M. Ylianttila, J. Makela, and P. Mahonen, "Supporting Resource Allocation with Vertical Handoffs in Multiple Radio Network Environment," *Proc. 13th IEEE Int'l Symp. Personal, Indoor and Mobile Radio Comm. (PIMRC '02),* pp. 64-68, Sept. 2002.

[9] H. Park, S. Yoon, T. Kim, J. Park, M. Do, and J. Lee, "Vertical Handoff Procedure and Algorithm between IEEE 802.11 WLAN and CDMA Cellular Network," *Proc. Seventh CDMA Int'l Conf. (CIC '02),* pp. 103-112, 2002.

[10] C.W. Lee, L.M. Chen, M.C. Chen, and Y.S. Sun, "A Framework of Handoffs in Wireless Overlay Networks Based on Mobile IPv6," *IEEE J. Selected Areas in Comm.,* vol. 23, no. 11, pp. 2118-2128, Nov. 2005.

[11] J. McNair and F. Zhu, "Vertical Handoffs in Fourth-Generation Multinetwork Environments," *IEEE Wireless Comm.,* vol. 11, pp. 8-15, June 2004.

[12] Z. Fang and J. McNair, "Optimizations for Vertical Handoff Decision Algorithms," *Proc. IEEE Wireless Comm. and Networking Conf. (WCNC '04),* vol. 2, pp. 867-872, Mar. 2004.

[13] B.-J. Chang, S.-Y. Lin, and Y.-H. Liang, "Minimizing Roaming Overheads for Vertical Handoff in Heterogeneous Wireless Mobile Networks," *Proc. Int'l Wireless Comm. and Mobile Computing Conf. (IWCMC '06),* pp. 957-962, July 2006.

[14] S. Mohanty and I.F. Akyildiz, "A Cross-Layer (Layer 2 + 3) Handoff Management Protocol for Next-Generation Wireless Systems," *IEEE Trans. Mobile Computing,* vol. 5, no. 10, pp. 1347-1360, Oct. 2006.

[15] V.V. Veeravalli and O.E. Kelly, "A Locally Optimal Handoff Algorithm for Cellular Communications," *IEEE Trans. Vehicular Technology,* vol. 46, no. 3, pp. 603-609, Aug. 1997.

[16] G.P. Pollini, "Trends in Handover Design," *IEEE Comm. Magazine,* vol. 34, no. 3, pp. 82-90, Mar. 1996.

[17] H. Maturino-Lozoya, D. Munoz-Rodriguez, and H. Tawfik, "Pattern Recognition Techniques in Handoff and Service Area Determination," *Proc. 44th Vehicular Technology Conf. (VTC '94),* vol. 1, pp. 96-100, 1994.

[18] W. Zhang, "Handover Decision Using Fuzzy MADM in Heterogeneous Networks," *Proc. IEEE Wireless Comm. and Networking Conf. (WCNC '04),* Mar. 2004.

[19] Q. Guo, J. Zhu, and X. Xu, "An Adaptive Multi-criteria Vertical Handoff Decision Algorithm for Radio Heterogeneous Network," *Proc. IEEE Int'l Conf. Comm. (ICC '05),* vol. 4, pp. 2769-2773, May 2005.

[20] S. Tang and W. Li, "Performance Analysis of the 3G Network with Complementary WLANs," *Proc. IEEE Global Telecomm. Conf. (GLOBECOM '05),* pp. 2637-2641, 2005.

[21] A.H. Zahran and B. Liang, "Performance Evaluation Framework for Vertical Handoff Algorithms in Heterogeneous Networks," *Proc. IEEE Int'l Conf. Comm. (ICC '05),* vol. 4, pp. 173-178, May 2005.

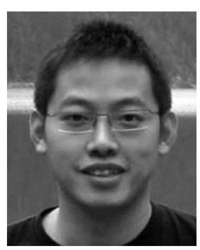
[22] V. Devarapalli, R. Wakikawa, A. Petrescu, and P. Thubert, *Network Mobility (NEMO) Basic Support Protocol,* IETF RFC 3963, Jan. 2005.

[23] M. Liu, Z.C. Li, X.B. Guo, E. Dutkiewicz, and D.K. Zhang, "Performance Evaluation of Vertical Handoff Decision Algorithms in Heterogeneous Wireless Networks," *Proc. IEEE Global Telecomm. Conf. (GLOBECOM '06),* Nov. 2006.

[24] E. Stevens-Navarro and V.W.S. Wong, "Comparison between Vertical Handoff Decision Algorithms for Heterogeneous Wireless Networks," *Proc. 63rd Vehicular Technology Conf. (VTC '06-Spring),* pp. 947-951, 2006.

Min Liu received the BS and MS degrees in computer science from Xi'an Jiaotong University, China, in 1999 and 2002, respectively. She is currently working toward the PhD degree in the Graduate University of the Chinese Academy of Sciences. She is also an associate professor in the Next-Generation Internet Research Center, Institute of Computing Technology (ICT), Chinese Academy of Sciences (CAS). Her research interests include mobile IP, handoff, network measurement, and mobile computing. She is a member of the IEEE.

Zhongcheng Li received the BS degree in computer science from Beijing University in 1983 and the MS and PhD degrees from the Chinese Academy of Sciences in 1986 and 1991, respectively. From 1996 to 1997, he was a visiting professor at the University of California, Berkeley. He is currently a professor in the Institute of Computing Technology, Chinese Academy of Sciences. His research interests include next-generation Internet, dependable systems and networks, and wireless communication. He has published more than 100 technical papers and is the holder of 10 patents. He is a member of the IEEE.



Xiaobing Guo received the BS and MS degrees in computer science from Xi'an Jiaotong University, China, in 1999 and 2002, respectively. He is currently the standard steering manager at the Collaborative Computing Laboratory, Lenovo Corporate Research and Development. He is also the chair of the Intelligent Grouping and Resource Sharing (IGRS) Technical Committee. His current research interests include mobile IP and device collaboration.

Eryk Dutkiewicz received the BE degree in electrical and electronic engineering and the MS degree in applied mathematics from the University of Adelaide in 1988 and 1992, respectively. He received the PhD degree in telecommunications from the University of Wollongong in 1996. He is currently a professorial fellow at the University of Wollongong, where he is in charge of the Wireless Technologies Laboratory. He holds visiting professorial appointments at the Chinese Academy of Sciences and the Shanghai Jiao Tong University. His current research interests include quality of service in broadband wireless networks and the optimization of wireless sensor networks. He has received Research Contract Awards in next-generation wireless technologies from Motorola Inc., USA, Agere Systems, Australia, and Freescale Semiconductor Inc., USA. He is a member of the IEEE.