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Performance evaluation of vertical handoff decision algorithms in heterogeneous wireless networks

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Abstract
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Keywords
Performance, evaluation, vertical, handoff, decision, algorithms, heterogeneous, wireless, networks

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Performance Evaluation of Vertical Handoff Decision Algorithms in Heterogeneous Wireless Networks

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Abstract—In recent years, many research works have focused on vertical handoff (VHO) decision algorithms. However, evaluation scenarios in different papers are often quite different and there is no consensus on how to evaluate performance of VHO algorithms. In this paper, we address this important issue by proposing an approach for systematic and thorough performance evaluation of VHO algorithms. Firstly we define the evaluation criteria for VHO with two metrics: matching ratio and average ping-pong number. Subsequently we analyze the general movement characteristics of mobile hosts and identify a set of novel performance evaluation models for VHO algorithms. Equipped with these models and evaluation criteria, we evaluate and analyze two types of decision algorithms: hysteresis based and dwelling-timer based algorithms. The results show a good match between simulation and analytical results.

Keywords—heterogeneous wireless networks, vertical handoff, horizontal handoff, performance evaluation

I. INTRODUCTION

Current wireless network technologies vary widely in terms of bandwidth, delay, coverage area, power consumption, etc. The next generation wireless networking (4G) is envisioned as a convergence of different wireless access technologies keeping the user connected to the best available access network [1].

Handoff (HO) is the mechanism by which an ongoing connection between a mobile terminal or host (MH) and a correspondent terminal or host (CH) is transferred from one point of access to the fixed network to another [2]. 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. In contrast, a vertical handoff is a handoff between access networks with different link layer technologies.

During the VHO procedure, handoff decision is the most important step that affects the normal working of communication [3]. An incorrect handoff decision may degrade the QoS of traffic and even break off current communication.

In wireless networks, signal quality and related metrics play an important role when deciding which interface to use. Traditional HHO algorithms are all based on the received signal strength (RSS) from the serving point of attachment and neighboring points of attachment [2]. Alternatively or in conjunction, the path loss, carrier-to-interference ratio (CIR), signal-to-interference ratio (SIR), bit error rate (BER) can also be used as a decision reference. In order to avoid the ping-pong effect, additional parameters such as threshold, hysteresis and dwelling timer can be used solely or jointly in the handoff decision process. In heterogeneous wireless networks, even though the functionalities of access networks are different, all the networks use a separate signal (beacon, BCCH, or reference channel) with a constant transmit power to enable RSS measurements for handoff decisions. Thus it is very natural and reasonable for VHO algorithms to use RSS as the basic criterion for handoff decision [4,5,6,7].

In order to evaluate performance of VHO algorithms, it is necessary to build reasonable and typical evaluation models. However, the evaluation scenarios used in different papers are quite different [5,6,7,8]. Many existing papers focusing on VHO use the simple movement scenario where MH traverses the coverage area of WLAN with a constant speed and unchanged direction. Some others just verify their algorithms with a prototype running in a simple experiment environment, in which it is impossible to accurately evaluate the influence of MH’s velocity on VHO performance.

In this paper, we firstly define the evaluation criteria for VHO. Then we analyze the general movement characteristics of MH and identify a set of novel performance evaluation models, which can reflect the characteristics of VHO and cover all handoff scenarios in heterogeneous wireless networks. With these models and criteria, we evaluate and analyze two types of decision algorithms proposed in the literature: hysteresis based and dwelling-timer based algorithm.

The rest of the paper is structured as follows. Section II presents the evaluation criteria for VHO algorithms. Section III identifies a set of novel performance evaluation models. Section IV evaluates and compares the performance of two traditional algorithms. The paper is concluded in section V.

II. EVALUATION CRITERIA FOR VHO ALGORITHMS

The degradation of the signal level is a random process and handoff algorithms based on signal strength measurements may cause the ping-pong effect. This takes a severe toll on both the user’s quality perception and the network load [2]. Thus a lot of mechanisms have been proposed to avoid unnecessary
handoff. However, these mechanisms may increase the handoff latency. If a handoff is delayed, weak signal reception will result in degradation of QoS and even break off current communication. Therefore there should be a tradeoff between these two aspects in handoff decision.

In order to evaluate the performance of VHO algorithms, we define two metrics: matching ratio and average ping-pong number.

Matching means the decision of the algorithm is the optimum network interface at the moment. For example, when the WLAN could provide better QoS, it is said to be matching if the algorithm chooses WLAN. The matching ratio (MR) is the percentage of the matching period per unit time. MR reflects QoS of the wireless link.

We define the ping-pong effect to occur when MH triggers two handoffs in a short time-scale (set 10s in our simulation). Average ping-pong number (APN) is the number of ping-pong effects per time unit. APN reflects the stability of the connection.

Based on the above definitions, high MR and low APN indicate high performance of the VHO algorithm.

III. PERFORMANCE EVALUATION MODELS FOR VHO ALGORITHMS

In this paper, we take GPRS and WiFi network as the representative of WWANs (Wireless Wide Area Networks) and WLANs (Wireless Local Area Networks) respectively. However, the proposed evaluation models are readily extensible to VHO between any other WWAN and WLAN.

A. Analysis of MH’s movement characteristics

There are four types of domains in the heterogeneous wireless network formed by GPRS and WiFi networks:

(I) Domain neither in the coverage area of GPRS nor in the coverage area of WiFi;

(II) Domain only in the coverage area of WiFi;

(III) Domain only in the coverage area of GPRS;

(IV) Domain in the overlapping coverage area of WiFi and GPRS. We separate this domain into two subdomains: domain (IV.W) (WiFi provides better QoS than GPRS); and domain (IV.G) (GPRS provides better QoS than WiFi).

Generally, the GPRS network can be assumed to support global coverage, in which WiFi segments are only small insulated islands. Thus in this paper, we assume MH only moves in domain (III) and domain (IV).

Based on MH’s movement characteristic, we classify the handoff scenarios into the traversing scenario and the roaming scenario. The former refers to when the MH moves from domain (IV.W), passes through domain (IV.G) and enters domain (III); or takes the reverse moving direction. The latter refers to when the MH moves back and forth around the boundary of domain (IV.W) and domain (IV.G). The traversing scenario has a simple and clear motion locus. Under this scenario, we can analyze the physical meaning of the handoff triggering condition and compare the handoff triggering locations in different VHO algorithms. It can also be used to evaluate the influence of certain parameters on VHO trigger. The roaming scenario forces the MH to make continuous handoffs. With this scenario, we can analyze and compare the integrative performance of VHO algorithms in frequent handoff cases.

B. Performance evaluation models

In order to evaluate performance of VHO algorithms, we design and implement four evaluation models. The former two are for the traversing scenario and the latter two are for the roaming scenario.

Assume the coverage area of WiFi is a circle whose centre is the AP. The velocity vector of MH can be separated into the radial component and the tangential component. The tangential component has no effect on signal strength and handoff trigger. Thus the simulation environment of VHO from GPRS to WiFi (G→W) can be reduced to the situation when MH takes one point at the boundary of domain (IV.G) and domain (III) as the origin, and moves towards AP by a uniform rectilinear motion with different speed. Assuming that at the staring point MH accesses Internet through GPRS, then with the movement of MH, different VHO decision algorithms will trigger G→W handoff at different locations.

Evaluation Model 1:

Assume the distance from MH to AP is $d$ and when $d=R$, MH is at the boundary of domain (IV.G) and domain (III). The motion equation of MH in model 1 can be expressed in polar coordinates as follows, where $(\rho, \theta)$ is the coordinate pair of MH, $t$ is the moving time, $v$ is the moving speed, and $maxv$ is the upper limit of $v$:

$$
\begin{align*}
\theta &= \frac{v}{\maxv} \pi \\
\rho &= R - vt 
\end{align*} 
$$

(1)

In one simulation, $v$ is set as a constant between $(0, \maxv]$. As $t$ increases, MH will make a uniform rectilinear motion from $(R, \theta)$ to $(-R, \theta)$. Fig.1 shows the motion loci of MH in model 1 for different $v$ in a polar coordinate system. By setting $v$ as different values, we can record and analyze the handoff locations of a VHO algorithm for different speed of MH.
We can also get the simulation environment of VHO from WiFi to GRPS (W→G) as shown in Fig.2. MH takes one point at the boundary of domain (IV.G) and domain (IV.W) as the origin, and moves away from AP by a uniform rectilinear motion. Assuming at the starting point MH accesses Internet through WiFi, then with the movement of MH, different VHO algorithms will trigger W→G handoff at different locations.

**Evaluation Model 2:**

Assume when $d = \varphi$, MH is at the boundary of domain (IV.G) and domain (IV.W). The motion equation of MH in model 2 can be expressed as follows, where the meaning of $\theta$, $\rho$, $v$, $t$ and $\text{max}v$ is the same as in equation (1):

\[
\begin{align*}
\theta &= \frac{v}{\text{max}v} \pi \\
\rho &= \varphi + vt \\
\end{align*}
\]

(2)

![Figure 2. Evaluation Model 2 illustration](image)

**Evaluation Model 3:**

The motion equation of MH in model 3 can be expressed as follows, where $\tau$ is defined as the amplitude and $2\pi / \mu$ is the period of the sinusoid:

\[
\rho = \varphi + \tau \sin \mu \theta
\]

(3)

Fig.3 shows the motion loci of MH with different values of $\tau$ and $\mu$. MH makes uniform motion without pause.

![Figure 3. Evaluation Model 3 illustration](image)

When $\mu$ is very small, the movement of MH will approximate a uniform circular motion around AP. As $\mu$ increases, MH will show an oscillation state with regular speed and displacement.

**Evaluation Model 4:**

In evaluation model 4, we set a square in domain (IV) with a side length of $a$ as shown in Fig.4. MH takes A as the origin point and after a sequence of random rectilinear motions, it reaches destination B.

![Figure 4. Evaluation Model 4 illustration](image)

We have presented a definition of random rectilinear motion in [9]: MH randomly chooses the moving speed and moving time. The moving speed $v$ satisfies a uniform distribution between (0, $\text{max}v$] and the moving time $t$ satisfies a uniform distribution between (0, $2a / \text{max}v$]. Then MH randomly chooses the destination in the square area and moves straight towards the destination with the constant speed until $t$ expires. If the MH reaches the destination before $t$ expires, it will randomly choose another destination and move straight towards the new destination with the previous speed until $t$ expires. When $t$ expires, MH will choose a new moving speed and moving time and then repeat the procedure.

In this model, the square in Fig.4 satisfies the following conditions: when MH makes a random rectilinear motion, the time expectation of its staying in domain (IV.W) is equal to the time expectation of its staying in domain (IV.G). We assume that the extension line of one diagonal of the square crosses the position of AP and the position coordinates of the square’s four vertices are $\{(u,u),(u+a,u),(u+a,u+a),(u,u+a)\}$. The numerical solution of $u$ can be obtained by the Monte Carlo method.

**IV. EVALUATION AND ANALYSIS OF HANDOFF DECISION ALGORITHMS**

With the proposed models and criteria, we evaluate and analyze two types of algorithms: hysteresis based algorithm (HY)[2][7] and dwelling-timer based algorithm (DW)[2][8]. In simulation we assume that when the RSS of GPRS and WiFi are the same, they provide the same QoS. Actually, RSS is not the only QoS factor. We will discuss how to define a more comprehensive and practical QoS in our future work.

Because GPRS network can be assumed to support global coverage, in signal strength measurement for handoff decision, the RSS of GPRS can be considered as a constant. We can only measure the RSS change of WiFi to trigger the handoff. As
defined before, when \( d = \varphi \), GPRS and WiFi provide the same QoS. Assume when \( d = \varphi \), the RSS of WiFi is \( RSS_0 \). We define that \( D_{RSS} = RSS_{WiFi} - RSS_0 \). Thus when \( d = \varphi \), \( D_{RSS} = 0 \).

Unless specified otherwise, the simulation parameters are as follows. \( h_y \) is the hysteresis in HY and \( t_{dw} \) is the dwelling-timer in DW. The coverage area of WiFi is a circle with a radius of \( R = 150 \text{m} \). The coordinates of AP are \((0, 0)\). Assume that when the distance from MH to AP is \( d = d^+ \), \( D_{RSS} = h_y \); when \( d = d^- \), \( D_{RSS} = h_y \). In simulations, set \( d^+ = 120 \text{m} \) and \( d^- = 135 \text{m} \). Thus \( \varphi = \sqrt{d^+ d^-} = 127.279 \text{m} \). The sampling interval in model 3 and model 4 is \( 0.05 \text{s} \). \( t_{dw} \) in DW is \( 5 \text{s} \).

A. Simulation results of evaluation model 1 & model 2

In Fig.5-Fig.8, we record the position coordinates of MH when handoffs are triggered by HY and DW in model 1 and 2, respectively. In these figures we assume the sampling interval is zero. When the decision reference change, VHO algorithm will trigger corresponding operations with no latency.

The theoretic handoff conditions of HY in model 1 should be: \( \rho = d^+ \) and \( 0 < \theta \leq \pi \), which has no relation with \( v \). The theoretic handoff conditions of DW in model 1 should be:

\[
\rho = \frac{\max v \cdot t_{dw} \cdot \theta}{\pi} \quad 0 < \theta \leq \min\left(\frac{2\pi \varphi}{\max v \cdot t_{dw}}, \pi\right) \quad (4)
\]

In (4), when \( \max v \cdot t_{dw} \) is larger than \( 2 \varphi \), the upper limit of \( \theta \) will be less than \( \pi \). In this case, if \( \theta > \frac{2\pi \varphi}{\max v \cdot t_{dw}} \), the MH will move out of domain (IV.W) during \( t_{dw} \), which means there is no need for G \( \rightarrow \) W handoff any more. In model 1, the handoff condition of DW is relative to \( \theta \), thus it will change with different \( v \).

The theoretic handoff conditions of HY in model 2 should be: \( \rho = d^- \) and \( 0 < \theta \leq \pi \). While the theoretic handoff conditions of DW in model 2 should be:

\[
\rho = \begin{cases} 
\phi + \frac{\max v \cdot t_{dw} \cdot \theta}{\pi} & 0 < \theta \leq \min\left(\frac{(R - \phi)\pi}{\max v \cdot t_{dw}}, \pi\right) \\
R & \frac{(R - \phi)\pi}{\max v \cdot t_{dw}} < \theta \leq \pi
\end{cases} \quad (5)
\]

HY is essentially a type of pure location-based decision algorithm. In contrast, DW can be considered as a type of location-and-time based algorithm, which decides whether to trigger a handoff based on the staying time in a specific domain. Fig.5-Fig.8 show a very good match between simulation and analytical results. As can be seen from Fig.8, when \( \max v = 20 \text{m/s} \), as \( \theta \) increases, the handoff trigger position of DW will be located in the circle of \( R = 150 \text{m} \). The reason is that when the moving speed of MH is high, DW can not trigger W \( \rightarrow \) G handoff in domain (IV,G) for the time requirement of \( t_{dw} \). Instead, DW will trigger handoff in domain (III) when the signal of WiFi is unavailable.

B. Simulation results of evaluation model 3

In the evaluation of HY and DW in model 3, we set \( \{\tau, \mu, v\} \) as \{15,5,1\}, \{10,5,1\}, \{15,10,1\} and \{15,5,10\}, and compare the latter three groups of simulation results with the first one, in which \( v \) is the speed of MH in m/s. Fig.9-Fig.10 show the MR and APN of these two handoff algorithms in one cycle, which
means the period from when MH starts moving, to when it returns to its starting point in model 3.

In the figures, **WiFi MR** means the time percentage of choosing WiFi when \( D_{\text{RSS}} > 0 \), while **GPRS MR** means the time percentage of choosing GPRS when \( D_{\text{RSS}} < 0 \). In the figures **GPRS MR** is higher than **WiFi MR**. This is because the region where \( D_{\text{RSS}} = 0 \) is farther from origin \((0, 0)\) and has a higher motion locus percentage in this model.

![Figure 9. Performance of HY in model 3 for different sets of \( \{r, \mu, v\} \)](image)

![Figure 10. Performance of DW in model 3 for different sets of \( \{r, \mu, v\} \)](image)

As shown in Fig.9, when \( r \) is small, performance of HY is poor. As \( r \) increases, its performance gets a remarkable improvement. In addition, the influence of speed on MR of HY is small. However, high speed will cause a serious ping-pong effect. In contrast, DW’s MR will reduce sharply as \( v \) increases. And the influence of \( r \) on DW is small. For both HY and DW, larger \( \mu \) will result in a relatively poorer MR.

### C. Simulation results of evaluation model 4

We set the side length of the square as \( a = 50m \). By the Monte Carlo method we can calculate that \( \mu = 64.61m \). We respectively set \( maxv = 2m/s \) and \( 20m/s \), and generate more than 1,000,000 groups of movement loci for MH. Table I and II show the results for the whole simulation. In the Tables, column GPRS means always choosing the GPRS network, while column WiFi means always choosing the WiFi network.

**TABLE I. PERFORMANCE EVALUATION IN MODEL 4 WITH maxv = 2m/s**

<table>
<thead>
<tr>
<th></th>
<th>HY</th>
<th>DW</th>
<th>GPRS</th>
<th>WiFi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WiFi MR(%)</strong></td>
<td>79.8</td>
<td>90.1</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td><strong>GPRS MR(%)</strong></td>
<td>78.1</td>
<td>90.1</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td><strong>Overall MR(%)</strong></td>
<td>79.0</td>
<td>90.1</td>
<td>50.2</td>
<td>49.8</td>
</tr>
<tr>
<td><strong>APN (1/100s)</strong></td>
<td>0.0044</td>
<td>0.14</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE II. PERFORMANCE EVALUATION IN MODEL 4 WITH maxv = 20m/s**

<table>
<thead>
<tr>
<th></th>
<th>HY</th>
<th>DW</th>
<th>GPRS</th>
<th>WiFi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WiFi MR(%)</strong></td>
<td>79.9</td>
<td>57.7</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td><strong>GPRS MR(%)</strong></td>
<td>78.1</td>
<td>58.4</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td><strong>Overall MR(%)</strong></td>
<td>79.0</td>
<td>58.1</td>
<td>50.0</td>
<td>50.0</td>
</tr>
<tr>
<td><strong>APN (1/100s)</strong></td>
<td>7.2</td>
<td>1.1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

When the speed is slow, the MR of HY is about 10% lower compared with DW, and the APN of both algorithms is small. However, when the average speed is 10m/s (\( maxv = 20m/s \)), the conclusions are quite different. Firstly, although the MR of HY changes little, its APN increases dramatically. \( APN \sim 7.2/100s \) means the MH comes into a severe ping-pong effect and cannot maintain normal communication. As far as DW is concerned, when \( maxv = 20m/s \), its APN only increases to 1.1/100s, which is an acceptable value. However, its total MR is only 58%, just 8% better than always choosing WiFi or GPRS without any VHO operations. To sum up, neither HY nor DW is suitable for the high speed movement environment.

**V. CONCLUSIONS AND FUTURE WORK**

In this paper, we defined the evaluation criteria for VHO and identified a set of novel performance evaluation models. With these models and criteria, we evaluated and analyzed two types of decision algorithms: hysteresis based algorithm (HY) and dwelling-timer based algorithm (DW). HY is essentially a type of pure location-based decision algorithm, which will get a similar matching ratio at different moving speeds. However, with the increase of MH’s moving speed, it will result in a serious ping-pong effect. In contrast, DW can be considered as a type of location-and-time based algorithm, whose matching ratio will reduce sharply when the moving speed increases.

In future work, we will extend the performance evaluation models to multi-user scenarios, and analyze the influence of the user number on VHO decisions.

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