A Performance Evaluation Model for RSS-based Vertical Handoff Algorithms

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Abstract

Many RSS-based vertical handoff algorithms have recently been proposed. However, there are only a few models to evaluate the performance of vertical handoff algorithms and none of the existing models reflect the effect of a doorway on received signal strength (RSS). Considering that RSS from heterogeneous networks cannot be directly compared with each other, we firstly present an effective method to compare RSS of different networks, based on the corresponding bandwidth in each network. Then, we take into account signal abrupt attenuation near a doorway and construct a novel performance evaluation model for RSS-based vertical handoff algorithms. This model also reflects the correlation between RSS at two adjacent locations in a WLAN. Following that, we propose an integrative performance evaluation function based on two metrics -- the decision delay and the number of handoffs. Furthermore, we analyze hysteresis and dwell-timer algorithms with our model. The results show a good match between simulation and analysis.

1. Introduction

Vertical handoffs (VHOs) are a major challenge to implementing the fourth generation (4G) system consisting of various heterogeneous wireless networks (WLANs, 3G networks, etc.). VHOs refer to handoffs between base stations (BSs) and access points (APs) using different wireless network technologies [1]. The VHO procedure comprises VHO decision and VHO execution.

VHO decision algorithms can be divided into two categories in terms of decision indicators. Some VHO algorithms use wireless link quality as the decision indicator, such as received signal strength (RSS), signal-to-noise ratios (SNR) and bit error ratios (BER). RSS-based VHO algorithms are typical of this category, judging when WLANs are available and can be selected for the basic quality of service (QoS). The other algorithms trigger VHOs based on available bandwidth, the network delay, cost of service, security, power consumption, user preference and so on. They are used to determine which network should be chosen for the best QoS in the case that more than one network is available.

A lot of RSS-based VHO algorithms have been proposed, such as the hysteresis algorithm [2], the dwell-timer algorithm [3], the SAVA [4] and the ALIVE-HO algorithm [5]. However, there are only a few systematic models to evaluate the performance of various algorithms [6], [7]. In [6], a common phenomenon in wireless networks, shadowing which leads VHO algorithms into a dilemma, is ignored in the proposed performance evaluation models. [7] presents a performance evaluation framework for VHO algorithms, but does not mention the abrupt signal decline caused by a doorway or physical obstructions.

WLANs are usually deployed in indoor environments, such as business centers, hotels and companies. Consequently, MTs need to trigger a VHO to 3G networks when they move out of the buildings. The sharp degradation of RSS from WLANs is likely to break off the current communication. It is significant for performance evaluation models to reflect VHO algorithms' capability of both resisting randomly fluctuant signal strength and responding rapidly to sharp degradation. In this research, we take into account the influence of signal fluctuation and abrupt attenuation on VHO algorithms. Moreover, we pay attention to the correlation between the strength of signals received at two adjacent locations from an AP.

The rest of this paper is organized as follows. In Section 2, we present a method of converting the bandwidth in 3G networks to equivalent RSS of WLANs. Section 3 proposes a systematic performance evaluation model. Then, two evaluation criteria are analyzed and an integrative performance evaluation function is given in Section 4. Section 5 discusses two types of traditional VHO algorithms, while simulation and analytical results are shown in Section 6, with some conclusions being provided in Section 7.

2. The Comparison of QoS in Heterogeneous

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Networks

RSS from WLANs and 3G networks cannot be directly compared with each other due to their heterogeneity. As a result, we need to search for a theoretical method of comparing QoS in WLANs and 3G networks by mapping RSS to another indicator.

Although there are various factors influencing user perceived QoS, users usually pay the most attention to network bandwidth. Therefore, we use network bandwidth to represent QoS. We only consider the case that there are sparse users in wireless networks. In the case, a user's available bandwidth merely depends on RSS on the assumption that noise strength is fixed. For the case that there are dense users in wireless networks, MTs should make use of two types of VHO algorithms together for more accurate VHO decisions.

In 3G networks, channels and time slots are allocated to a MT beforehand by its BS, so it can be assumed that the bandwidth is constant when the MT moves within hundreds of meters. In 802.11 systems, the data rate is chosen based on the achievable RSS to meet a certain link quality, so the bandwidth is dynamic. In view of these, we present a method for comparing QoS in both networks based on the relation between RSS and bandwidth.

RSS from the WLAN is composed of two parts.

$$RSS_W(d) = \mu_{RSS}(d) + \xi(\sigma, d) \tag{1}$$

Here, d is the distance between the MT and the AP (in meters). $\xi(\sigma,d)$, representing shadowing effect, denotes a zero mean Gaussian random variable with standard deviation σ when the MT is d meters away from the AP. The average signal strength, $\mu_{RSS}(d)$, is a function of d.

$$\mu_{RSS}(d) = K - P_L(d)$$

where K is a parameter about the transmitted power, the transmitting / receiving antenna gain and the transmitting / receiving coax loss, as well as $P_L(d)$ is the path loss.

We define S_R as receiver sensitivity, which is a measurement of the weakest signal that a receiver can correctly translate into data. As a result, the probability that the MT in the WLAN can receive data is

$$P\{RSS_W(d) > S_R\} = 1 - \Phi\left(\frac{S_R - \mu_{RSS}(d)}{\sigma}\right)$$

where $\Phi(\bullet)$ is the cumulative distribution function of the standardized normal random variable.

The data rate in the WLAN is a function of $\mu_{RSS}(d)$.

$$DR_W(\mu_{RSS}(d)) = \begin{cases} r_1, \mu_{RSS}(d) \in (-\infty, S_1) \\ r_2, \mu_{RSS}(d) \in [S_1, S_2) \\ \vdots \\ r_m, \mu_{RSS}(d) \in [S_{m-1}, \infty) \end{cases}, r_1 < r_2 < \cdots < r_m$$

where $S_1, S_2, \ldots, S_{m-1}$ are receiver sensitivity values required for different levels of data rates from r_2 to r_m.

The bandwidth in the WLAN can be computed as

$$B_W(d) = P\{RSS_W(d) > S_R\} DR_W(\mu_{RSS}(d))$$

Since $B_W(d)$ is a non-continuous increasing function of $\mu_{RSS}(d)$ and the bandwidth in the 3G network, B_G, is smaller than r_m, it can be proved that

$$\exists RSS_W \in R, B_W(d)|_{\mu_{RSS}(d)=RSS_W^-} < B_G \le B_W(d)|_{\mu_{RSS}(d)=RSS_W} \tag{2}$$

We define the RSS_W satisfying the formula (2) as the converted RSS of the 3G network, written as RSS_G, and can calculate it by solving the inequality.

We do not use actual RSS from 3G networks, but convert the bandwidth in 3G networks to the equivalent RSS of WLANs. Equipped with this method, we can compare the actual RSS from WLANs with the converted RSS of 3G networks.

3. An Evaluation Model

In this section, we present a novel performance evaluation model for VHO algorithms after briefly describing the movement mode of a MT. The model assumes that a MT passes through a doorway from a building to the outside or reverses.

We adopt a simplified movement model, where a MT moves away from its AP in a straight line at a constant speed V (in meters per second) until it can receive no signal of the AP or moves reversely at the same speed. We concentrate on the overlapping annular coverage area of the WLAN and the 3G network, where $RSS_W(d)$ is a little stronger or weaker than RSS_G. d_{min} and d_{max} are the minimal and maximal distances between the AP and the MT in this domain, respectively. Sampling $RSS_W(d)$ at equally spaced time intervals, T (in seconds), we get the sequences of $RSS_W[i]$.

Compared to the limited coverage of WLANs, the 3G network can be assumed to support global coverage and to have constant RSS, denoted by RSS_G. However, RSS of WLANs is greatly complicated. We need to study $\mu_{RSS}(d)$ and $\xi(\sigma,d)$ separately.

Firstly, the function, $\mu_{RSS}(d)$, is constituted of two pieces: the indoor and outdoor average signal strength.

As usual, we use the log-linear model in (3) to represent the path loss of indoor signals [8].

$$P_L(d) = 32.5 + 20\log_{10} F + 10 n_I \log_{10} d \tag{3}$$

where F is the frequency of 802.11 systems (in GHz) and n_I is the path loss exponent for indoor environments.

Let $C = K - 32.5 - 20\lg F$

Then, the indoor average signal strength of the WLAN is $\mu_{RSS}(d) = C - 10 n_I \log_{10} d, d \in [0, d_d]$, where d_d is the distance between the door and the AP.

Unlike indoor signals, outdoor signals are combinations of two parts. On one hand, the signals penetrating through the wall attenuate by 5dB to 30dB, depending on the material of the wall. On the other hand, the wavelength of 802.11b/g signals, 0.125m, is of the same order of magnitude as the width of a door, ordinarily from 0.5m to 1m. Therefore, one-slot diffraction happens outside the building and the diffracted signals propagate in various directions.

The strength of penetrating signals can be expressed as

$$RSS_{Pe}(d) = C - 10n_I \log_{10} d_d - O_L - 10n_O \log_{10}(d / d_d)$$

where O_L is the obstacle loss caused by the wall, and n_O is the path loss exponent for outdoor environments.

The strength of diffracted signals can be expressed as

$$RSS_{Di}(d) = C - 10n_I \log_{10} d_d - 10n_O \log_{10}(d - d_d + 1)$$

Thus, the outdoor average signal strength of the WLAN is

$$\mu_{RSS}(d) = 10\log_{10}\left(10^{RSS_{Pe}(d)/10} + 10^{RSS_{Di}(d)/10}\right), d \in [d_d, \infty)$$

Secondly, we take the random process, $\xi(\sigma,d)$, into account. $\xi(\sigma,d)$, caused by sporadic obstacles, is unlikely to change abruptly when the MT moves from one position to another adjacent position, so the autocorrelation coefficient [9] between $\xi(\sigma,d_1)$ and $\xi(\sigma,d_2)$ is assumed to be

$$\rho_{\xi(\sigma,d_1),\xi(\sigma,d_2)} = \rho^{|d_1-d_2|}, \rho \in (0,1), d_1, d_2 \in [d_{\min}, d_{\max}] \quad (4)$$

From (1) and (4), the correlation coefficient between $RSS_W(d_1)$ and $RSS_W(d_2)$ is

$$\rho_{RSS_W(d_1),RSS_W(d_2)} = \frac{Cov(RSS_W(d_1), RSS_W(d_2))}{\sigma^2} = \rho^{|d_1-d_2|}$$

We have $\mu_{RSS}[i] = \mu_{RSS}(VTi)$ and $\rho_{RSS_W[i],RSS_W[i-j]} = \rho^{VTj}$ (5)

Hence, the random vector ($RSS_W[i]$, $RSS_W[i\text{-}1]$,…, $RSS_W[i\text{-}n\text{+}1]$) has a multivariate normal distribution and its joint probability density function is defined by (5).

4. Evaluation Criteria

In this section, we firstly analyze two metrics -- the decision delay and the number of handoffs, and then give an integrative performance evaluation function based on these two criteria.

4.1. The Decision Delay and the Number of Handoffs

Statistically, it is ideal that VHOs happen at the position where $\mu_{RSS}(d)$ equals RSS_G. The decision delay is defined as the time after the optimal handoff location that it takes for the VHO to occur [10]. If a VHO occurs before the optimal handoff point is reached, it is assigned a negative value. The MT reaches the optimal handoff location at the i_{OHO} th sampling instant. The first and last VHOs are triggered at the I_{FHO} th and I_{LHO} th instants, respectively. Accordingly, the first-handoff decision delay is the time after the i_{OHO} th instant at the I_{FHO} th instant, and the last-handoff decision delay is the time after the i_{OHO} th instant at the I_{LHO} th instant. The interval between the first and last VHOs is more than zero if multiple back-and-forth VHOs occur. In order to make this criterion immune to the ping-pong effect, we estimate the decision delay with the mean of the first-handoff and last-handoff decision delays as the following equation.

$$\begin{aligned} D &= T\left(\frac{E\{I_{FHO}\} + E\{I_{LHO}\}}{2} - i_{OHO}\right) \\ &= T\left(\frac{1}{2}\sum_{i=1}^{i_{\max}} i \cdot f_{I_{FHO}}(i) + \frac{1}{2}\sum_{i=1}^{i_{\max}} i \cdot f_{I_{LHO}}(i) - i_{OHO}\right) \end{aligned} \quad (6)$$

where $f_{I_{FHO}}(i)$ and $f_{I_{LHO}}(i)$ are the probability density functions of I_{FHO} and I_{LHO}, respectively.

The number of handoffs is referred to as the number of VHOs when the MT moves out of or into the WLAN in a fixed direction. In our model, the expected number of handoffs is computed as

$\overline{N_{HO}} = E\{N_{HO}\} = \sum_{i=0}^{i_{\max}} P_{HO}[i]$ (7), where $P_{HO}[i]$ is the probability that a VHO occurs at the i th sampling instant.

Note that in a WLAN, the correlation between RSS at two adjacent locations smoothes away frequent abrupt changes of RSS. For this reason, the number of handoffs decreases when correlation coefficients are introduced into our signal model.

4.2. An Integrative Performance Evaluation Function

It is crucial for VHO algorithms to make a tradeoff between triggering necessary handoffs in time and avoiding the ping-pong effect, but the significance of both criteria depends on specific scenarios. Thus, in the performance evaluation of VHO Algorithms, we have to distinguish dissimilar VHO scenarios, and divide them into two categories: signal fluctuation scenarios and signal attenuation scenarios. For the former, the number of handoffs is more important than the decision delay. For the latter, the case is reverse. Hence, we propose the integrative performance evaluation function as follows.

$P_{total} = \frac{100}{(VD)^{1-W}}\left(\frac{\sigma}{\overline{N_{HO}}}\right)^W$ (8), where $W = \frac{1}{\mu'_{RSS}(d_{OHO})^2 + 1}$

Here, d_{OHO} is the distance between the AP and the optimal handoff position, and $\mu'_{RSS}(d_{OHO})$ is the right derivative of the function $\mu_{RSS}(d)$ when d equals d_{OHO}.

For VHO scenarios, the more steeply the signal changes, the smaller the weight, W, is. With W decreasing, the decision delay plays a greater role in the integrative performance of VHO algorithms. Hence, the evaluation function correctly describes the difference among VHO scenarios.

5. Performance Analysis of VHO Algorithms

Equipped with the proposed model, we analyze and evaluate the performance of dwell-timer (DT) and hysteresis (HY) algorithms in the case of the MT moving out of the WLAN. The case of the MT moving into the WLAN can be analyzed in the same way.

5.1. The Dwell-Timer Algorithm

In the DT algorithm, a counter of the samples of the RSS is started when a condition is true. The condition can be that the RSS from a BS/AP in another network exceeds the RSS from the current AP/BS. If the condition continues to be true until the value of the counter equals a predefined threshold, Dw, a VHO is initiated.

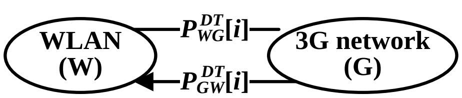

Figure 1. The Markov chain for the DT algorithm

Since the condition in the DT algorithm includes part of the history of RSS, the Markov chain with binary states in Figure 1 can roughly represent the handoffs between WLANs and 3G networks.

The transition probabilities can be computed as

$$P^{DT}_{WG}[i] = \Pr\{RSS_W[j] < RSS_G, \forall j \in [i - Dw + 1, i] \mid RSS_W[j - Dw] \geq RSS_G, \exists j \in [i - Dw, i - 1]\}$$

$$P^{DT}_{GW}[i] = \Pr\{RSS_W[j] > RSS_G, \forall j \in [i - Dw + 1, i] \mid RSS_W[j - Dw] \leq RSS_G, \exists j \in [i - Dw, i - 1]\}$$

Then, the state probabilities ${P_W}^{DT}[i]$ and ${P_G}^{DT}[i]$ can be calculated recursively, and accordingly $f_{IFHO}(i)$, $f_{ILHO}(i)$ and $P_{HO}[i]$ of the DT algorithm can be determined. Therefore, the decision delay and the number of handoffs of the DT algorithm can be worked out with (6) and (7).

5.2. The Hysteresis Algorithm

The HY algorithm means that a VHO is made if the RSS from a BS/AP in another network reaches or exceeds the RSS from the current AP/BS by a hysteresis margin.

Although the network selection of the HY algorithm only depends on the current network and the current RSS, its analysis cannot be based on the model in Figure 1, because the current RSS correlates with earlier RSS at adjacent locations. Since the sequence of chosen networks in the past implicitly embodies earlier RSS, we construct a 2^m state Markov chain (as shown in Figure 2, where m is 4) to represent the main history of chosen networks. Each state is expressed by the selected networks at the latest m sampling instants. The state at the i th instant is the sequence $N_{i-m+1}N_{i-m+2}...N_i$, where

$$N_i = \begin{cases} 1, \text{in the WLAN at the } i \text{ th instant} \\ 0, \text{in the 3G network at the } i \text{ th instant} \end{cases}$$

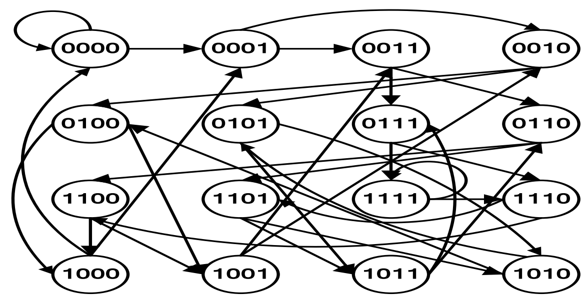

Figure 2. The Markov chain for the HY algorithm

The transition probabilities and the state probabilities can also be computed, but the details are omitted due to space limitations. Consequently, the decision delay and the number of handoffs of the HY algorithm can be obtained in the same way as the DT algorithm.

6. Simulation and Numerical Results

In addition to the above analysis, we have simulated two existing VHO algorithms using MATLAB. Here, we also take moving out of WLANs for example. The values of all parameters are shown in Table 1.

Table 1. Parameter values

Parameter	Value	Parameter	Value
K	20.1 dBm	T	0.1 s
F	2.4 Hz	B_G	2.4 Mbps
ρ	0.8	d_{min}	15 m
n_I	3.2	d_{max}	120 m
n_O	3.5	S_R	-94 dBm

According to the description of the Orinoco Gold (Hermes) 802.11b wireless card in [8], we prescribe that

$$DR_W(\mu_{RSS}(d)) = \begin{cases} 1Mbps, \mu_{RSS}(d) \in (-\infty, -91dBm) \\ 2Mbps, \mu_{RSS}(d) \in [-91dBm, -87dBm) \\ 5.5Mbps, \mu_{RSS}(d) \in [-87dBm, -82dBm) \\ 11Mbps, \mu_{RSS}(d) \in [-82dBm, \infty) \end{cases}$$

Therefore, RSS_G equals -87dB based on the method in Section 2 and the above-mentioned parameters.

6.1. The Signal Fluctuation Scenario

In the simulations, we generate 10000 sequences of $RSS_W[i]$ with our model where d_d equals 20m and O_L equals 7dB. For each group of RSS, the MT triggers VHOs according to the HY and DT algorithms separately. From our simulation and numerical results, we can see the performance of the HY and DT algorithms in the signal fluctuation scenario in Figure 3, 4, 5.

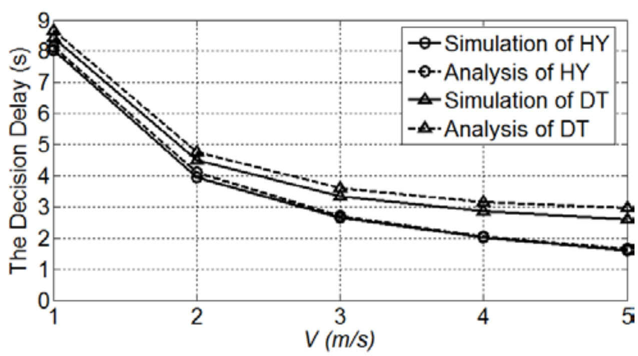

Figure 3. The decision delay vs. velocity (σ = 8dB, d_d = 20m, O_L = 7dB)

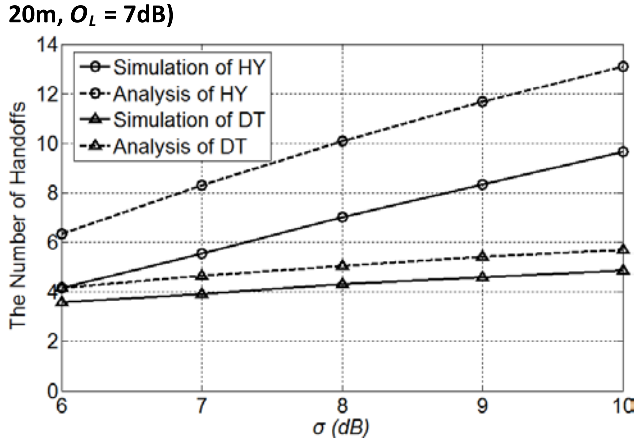

Figure 4. The number of handoffs vs. shadow standard deviation (V = 2m/s, d_d = 20m, O_L = 7dB)

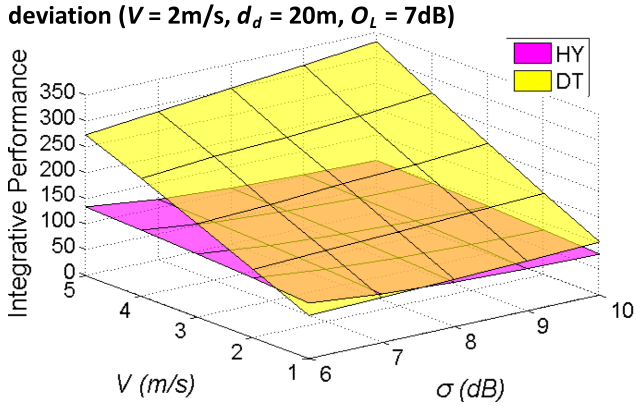

Figure 5. The integrative performance of algorithms (d_d = 20m, O_L = 7dB)

Figure 3 illustrates a great impact of the velocity on the decision delay when σ is 8dB. Clearly, the decision delay diminishes with the velocity, because RSS decreases rapidly under the high speed. Typically, the decision delay of the HY algorithm is in approximately inverse proportion to the speed. In addition, with the increase in the velocity, the correlation between two close samples of RSS decreases and the condition in the DT algorithm is not easily satisfied. Thus, the DT algorithm underperforms the HY algorithm in terms of the decision delay.

Figure 4 displays the influence of σ on the number of handoffs when V is 2m/s. From the figure, it can be seen that the number of handoffs increases almost linearly with σ. The same figure also demonstrates that the HY algorithm gives rise to a more serious ping-pong effect than the DT algorithm. In the figure, the change trend of numerical results is consistent with simulation results, even though the analytical approximations lead to errors between simulation and numerical results. Note the errors will become smaller if the adopted model has more states to record the history of RSS.

From Figure 5, we can observe the integrative performance of both algorithms in the signal fluctuation scenario. The results are calculated with (8) after the decision delay and the number of handoffs are obtained in simulations. The figure shows the integrative performance of the DT algorithm exceeds that of the HY algorithm, for the reason that the number of handoffs is of more importance than the decision delay when W is 0.9087.

6.2. The Signal Attenuation Scenario

With our model, we also generate 10000 groups of $RSS_W[i]$ under the conditions that d_d equals 50m and O_L equals 30dB. Figure 6, 7 and 8 show the performance of both algorithms when RSS declines steeply. Here, errors between simulation and numerical results are also caused by random errors in simulations and the analytical approximations.

Figure 6 plots the decision delay over different velocities, where σ equals 8dB. For the DT algorithm, the decision delay mainly depends on the dwell time and changes slightly under different speeds. For the HY algorithm, the decision delay is in approximately inverse proportion to the logarithm of the speed, because $\mu_{RSS}(d)$ decreases logarithmically with d near the doorway. Additionally, the HY algorithm responds to the rapid change of RSS earlier than the DT algorithm.

Figure 7 reveals the number of handoffs over different shadow standard deviations, where V equals 2m/s. Clearly, the number of handoffs increases when the shadowing effect becomes more severe. Besides, the DT algorithm initiates fewer handoffs than the HY algorithm.

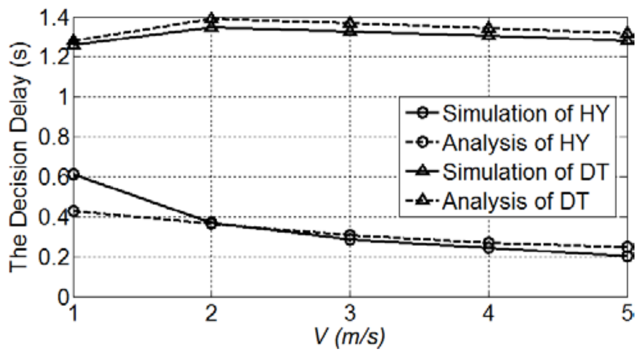

Figure 6. The decision delay vs. velocity (σ = 8dB, d_d = 50m, O_L = 30dB)

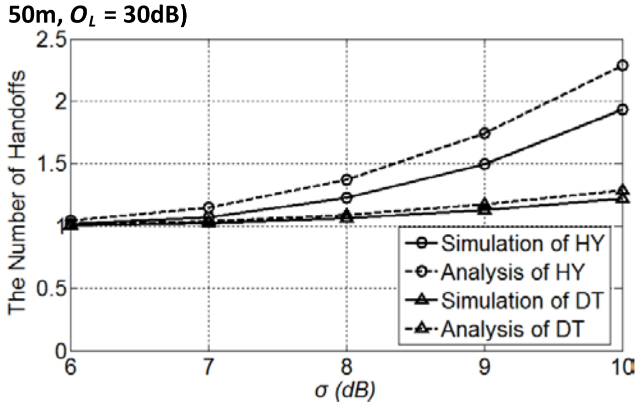

Figure 7. The number of handoffs vs. shadow standard deviation (V = 2m/s, d_d = 50m, O_L = 30dB)

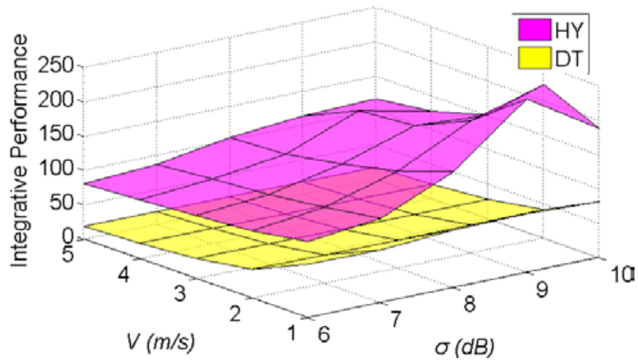

Figure 8. The integrative performance of algorithms (d_d = 50m, O_L = 30dB)

Figure 8 describes the integrative performance of these two algorithms in the signal attenuation scenario, which is obtained in the same way as Figure 5. In contrary to the signal fluctuation scenario, the integrative performance of the HY algorithm is higher than that of the DT algorithm in the signal attenuation scenario, as the decision delay dominates in the case that W in (8) is 0.0225.

7. Conclussions

In this paper, we present a feasible method of converting RSS of each network to the corresponding bandwidth for comparing RSS of different networks. We also propose a systematic and theoretical performance evaluation model for RSS-based VHO algorithms. The proposed model shows the effect of a doorway on RSS from WLANs and also reflects the correlation between the strength of signals received at two adjacent locations from a WLAN. Then, we give an integrative performance evaluation function based on analyzing the decision delay and the number of handoffs. Equipped with the proposed model and function, we evaluate the performance of hysteresis and dwell-timer algorithms. It is concluded that the hysteresis algorithm is suitable for signal attenuation scenarios and the dwell-timer algorithms is appropriate to signal fluctuation scenarios. Simulation and analytical results confirm that our model can be used to evaluate the performance of RSS-based VHO algorithms in the real world.

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