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A survey of vertical handover decision algorithms in Fourth Generation heterogeneous wireless networks

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ABSTRACT

Vertical handover decision (VHD) algorithms are essential components of the architecture of the forthcoming Fourth Generation (4G) heterogeneous wireless networks. These algorithms need to be designed to provide the required Quality of Service (QoS) to a wide range of applications while allowing seamless roaming among a multitude of access network technologies. In this paper, we present a comprehensive survey of the VHD algorithms designed to satisfy these requirements. To offer a systematic comparison, we categorize the algorithms into four groups based on the main handover decision criterion used. Also, to evaluate tradeoffs between their complexity of implementation and efficiency, we discuss three representative VHD algorithms in each group.

1. Introduction

Growing consumer demand for access to communication services anywhere and anytime is accelerating the technological development towards the integration of various wireless access technologies, nowadays called as Fourth Generation (4G) wireless systems [2]. 4G wireless systems will provide significantly higher data rates, offer a variety of services and applications previously not possible due to speed limitations, and allow global roaming among a diverse range of mobile access networks [12,33,15,52,20,44].

In a typical 4G networking scenario, handsets or mobile terminals with multiple interfaces will be able to choose the most appropriate access link among the available alternatives (these include IEEE 802.11 Wireless Local Area Network (WLAN) [13], IEEE 802.16 Worldwide Interoperability for Microwave Access (WiMAX) [45]), satellite systems [5] and Bluetooth [38], in addition to the traditional cellular telephony networks which are almost universally accessible today. For a satisfactory user experience, mobile terminals must be able to seamlessly transfer to the "best" access link among all available candidates with no perceivable interruption to an ongoing conversation (which could be a voice or video session). Such ability to hand over between heterogeneous networks is referred to as seamless vertical handovers [30]. As an important step towards achieving this objective, the emerging IEEE 802.21 standard creates a framework to support protocols for enabling seamless vertical handovers [42]. Since the 802.21 provides only the overall framework, the actual algorithms to be implemented are left to the designers. To fill this gap, numerous vertical handover decision (VHD) algorithms have been proposed in the research literature.

A number of studies published earlier have surveyed VHD algorithms [28,53,41]. In the earliest one [28], a tutorial on the design and performance issues of VHD policies is presented along with analysis and comparison of several VHD algorithms. However, the focus of this study was quite narrow and only covered cost function and received signal strength (RSS) based VHD algorithms. In a later study [53], the authors presented a framework to compare the performance of different vertical handover algorithms on system resource utilization and Quality of Service (QoS) perceived by users, but only included the evaluation

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of two VHD algorithms. A subsequent survey's focus [41] was on various mathematical models used in vertical handover decisions. In our paper, we approach this task by classifying the VHD algorithms into four groups, and offering a comparative analysis of selected three representative algorithms in each group. We also update these earlier studies by incorporating recently published algorithms into this survey.

2. Vertical handovers

2.1. Overview of handover processes and vertical handovers

Handover is the process of maintaining a user's active sessions when a mobile terminal changes its connection point to the access network (called "point of attachment"), for example, a base station or an access point [1]. Depending on the access network that each point of attachment belongs to, the handover can be either horizontal or vertical [32]. A horizontal handover takes place between points of attachment supporting the same network technology, for example, between two neighboring base stations of a cellular network. On the other hand, a vertical handover occurs between points of attachment supporting different network technologies, for example, between an IEEE 802.11 access point and a cellular network base station.

A handover process can be split into three stages: handover decision, radio link transfer and channel assignment [1]. Handover decision involves the selection of the target point of attachment and the time of the handover. Radio link transfer is the task of forming links to the new point of attachment, and channel assignment deals with the allocation of channel resources.

VHD algorithms help mobile terminals to choose the best network to connect to among all the available candidates. Here, we only focus on the research efforts and recent developments on improving the efficiency of VHD process. In contrast to horizontal handover decision algorithms which mainly consider RSS as the only decision criterion, for VHD algorithms, criteria such as cost of services, power consumption and velocity of the mobile terminal may need to be taken into consideration to maximize user satisfaction [32].

2.2. VHD criteria

Several parameters as shown in Fig. 1 have been proposed in the research literature for use in the VHD algorithms. We briefly explain each of them below.

Received signal strength (RSS) is the most widely used criterion because it is easy to measure and is directly related to the service quality. There is a close relationship between the RSS readings and the distance from the mobile terminal to its point of attachment. Majority of existing horizontal handover algorithms use RSS as the main decision criterion, and RSS is an important criterion for VHD algorithms as well.

Network connection time refers to the duration that a mobile terminal remains connected to a point of attachment. Determining the network connection time is very important for choosing the right moment to trigger a handover so that the service quality could be maintained at a satisfactory level. For example, a handover done too early from a WLAN to a cellular network would waste network resources while being too late would result in a handover failure. Determining the network connection time is also important for reducing the number of superfluous handovers, as handing over to a target network with potentially short connection time should be discouraged. The network connection time is related to a mobile terminal's location and velocity. Both the distance from the mobile terminal to its point of attachment and the velocity of the mobile terminal affect the RSS at the mobile terminal. The variation of the RSS then determines the time for which the mobile terminal stays connected to a particular network. Network connection time is especially important for VHD algorithms because heterogeneous networks usually have different sizes of network coverage.

Available bandwidth is a measure of available data communication resources expressed in bit/s. It is a good indicator of traffic conditions in the access network and is especially important for delay-sensitive applications.

Power consumption becomes a critical issue especially if a mobile terminal's battery is low. In such situations, it would be preferable to handover to a point of attachment which would help extending valuable battery life [32].

Monetary cost: For different networks, there would be different charging policies, therefore, in some situations the cost of a network service should be taken into consideration in making handover decisions.

Security: For some applications, confidentiality or integrity of the transmitted data can be critical. For this reason, a network with higher security level may be chosen over another one which would provide lower level of data security.

User preferences: A user's personal preference towards an access network could lead to the selection of one type of network over the other candidates.

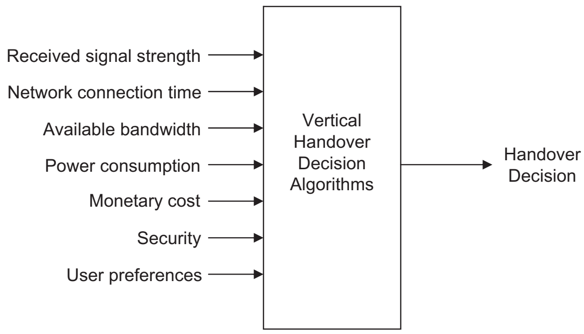

Fig. 1. Parameters used for making VHD decisions.

RSS and network connection time based decision criteria are widely used in both horizontal and vertical handover decisions. Others are mainly seen in VHD schemes only.

2.3. Classification of VHD algorithms

There are various ways to classify VHD algorithms [21,26]. In this article, we have chosen to divide VHD algorithms into four groups based on the handover decision criteria used and the methods used to process these.

RSS based algorithms: RSS is used as the main handover decision criterion in this group. Various strategies have been developed to compare the RSS of the current point of attachment with that of the candidate point of attachment [54,29,48]. In [37] RSS based horizontal handover decision strategies are classified into the following six subcategories: relative RSS, relative RSS with threshold, relative RSS with hysteresis, relative RSS with hysteresis and threshold, and prediction techniques. For VHD, relative RSS is not applicable, since the RSS from different types of networks can not be compared directly due to the disparity of the technologies involved. For example, separate thresholds for each network. Furthermore, other network parameters such as bandwidth are usually combined with RSS in the VHD process.

Bandwidth based algorithms: Available bandwidth for a mobile terminal is the main criterion in this group [22,51,10]. In some algorithms, both bandwidth and RSS information are used in the decision process [54,16]. Depending on whether RSS or bandwidth is the main criterion considered, an algorithm is classified either as RSS based or bandwidth based.

Cost function based algorithms: This class of algorithms combine metrics such as monetary cost, security, bandwidth and power consumption in a cost function, and the handover decision is made by comparing the result of this function for the candidate networks [56,18,43]. Different weights are assigned to different input metrics depending on the network conditions and user preferences.

Combination algorithms: These VHD algorithms attempt to use a richer set of inputs than the others for making handover decisions. When a large number of inputs are used, it is usually very difficult or impossible to develop analytical formulations of handover decision processes. Due to this reason, researchers apply machine learning techniques to formulate the processes. Our literature survey reveals that fuzzy logic and artificial neural networks based techniques [55,35] are popular choices. Fuzzy logic systems allow human experts' qualitative thinking to be encoded as algorithms to improve the overall efficiency. Examples of applying this approach into VHD can be found in [47,6,55,19,25]. If there is a comprehensive set of input-desired output patterns available, artificial neural networks can be trained to create handover decision algorithms [17,31,35]. It is also possible to create adaptive versions of these algorithms. By using continuous and real-time learning processes, the systems can monitor their performance and modify their own structure to create highly effective handover decision algorithms.

2.4. Performance evaluation metrics for VHD algorithms

VHD algorithms can be quantitatively compared under various usage scenarios by measuring the mean and maximum handover delays, the number of handovers, the number of failed handovers due to incorrect decisions, and the overall throughput of a session maintained over a typical mobility pattern. These metrics are further explained below:

Handover delay refers to the duration between the initiation and completion of the handover process. Handover delay is related to the complexity of the VHD process, and reduction of the handover delay is especially important for delay-sensitive voice or multimedia sessions.

Number of handovers: Reducing the number of handovers is usually preferred as frequent handovers would cause wastage of network resources. A handover is considered to be superfluous when a handover back to the original point of attachment is needed within a certain time duration [11,48], and such handovers should be minimized.

Handover failure probability: A handover failure occurs when the handover is initiated but the target network does not have sufficient resources to complete it, or when the mobile terminal moves out of the coverage of the target network before the process is finalized. In the former case, the handover failure probability is related to the channel availability of the target network [46], while in the latter case it is related to the mobility of the user [4].

Throughput: The throughput refers to the data rate delivered to the mobile terminals on the network. Handover to a network candidate with higher throughput is usually desirable.

3. Vertical handover decision algorithms

In this section, we discuss a representative set of VHD algorithms. Their operational fundamentals are summarized along with their comparative advantages and disadvantages. These algorithms are assigned into one of the four categories described in Section 2.3 (as shown in Fig. 2). Some of the algorithms use more than one VHD criteria, and in such cases, we consider the main criterion they use for classification.

3.1. RSS based VHD algorithms

RSS based VHD algorithms compare the RSS of the current point of attachment against the others to make handover decisions. Because of the simplicity of the hardware required for RSS measurements, not surprisingly, a large number of studies have been conducted in this area [36,27,54,29,48,7]. We describe three representative RSS based VHD algorithms in the following sections and present a comparative summary of them in Table 1.

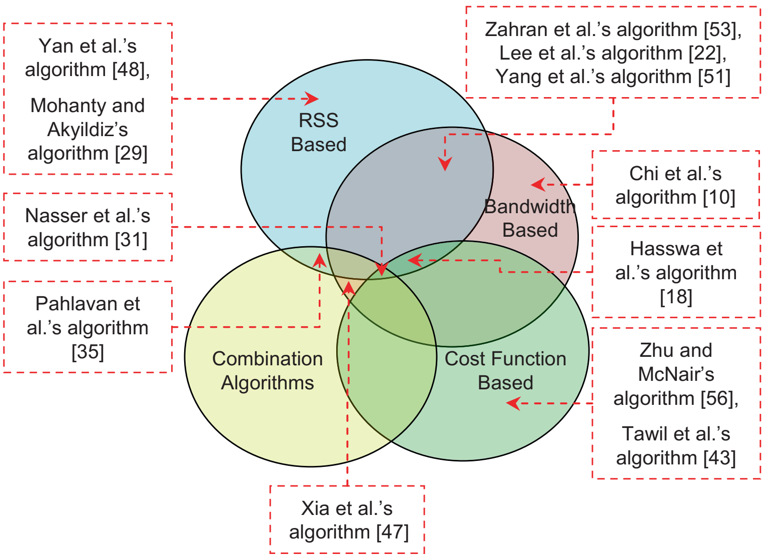

Fig. 2. The four categories of VHD algorithms and twelve selected representative schemes.

Table 1
A summary of RSS based VHD algorithms.

Heuristic	Applicable area	Feature	Advantages	Disadvantages
Zahran et al.'s heuristic [53]	Between 3G and WLANs	The RSS is combined with an estimated lifetime or the available bandwidth to decide the handover time	• Adaptation to application requirements and user mobility • Improvement on the available bandwidth	• Long packet delay • Extra lookup table
Mohanty and Akyildiz's heuristic [29]	Between 3G and WLANs	A dynamic RSS threshold is calculated and compared with the current RSS to determine the handover time from WLAN to 3G	• Reduction of the false handover initiation and handover failure probabilities	• Increased handover failure probability from 3G to WLAN • Wastage of network resources
Yanet al.'s heuristic [48]	Between cellular networks and WLANs	A dynamic time threshold is calculated and compared with the predicted traveling time inside the WLAN to help with handover decisions	• Minimization of the handover failure, unnecessary handover and connection breakdown probabilities	• Extra handover delay

3.1.1. An adaptive lifetime based handover heuristic

Zahran and Liang [54] proposed an algorithm for handovers between 3G networks and WLANs by combining the RSS measurements either with an estimated lifetime metric (expected duration after which the mobile terminal will not be able to maintain its connection with the WLAN) or the available bandwidth of the WLAN candidate. We describe their method through the following scenarios.

In the first scenario, when the mobile terminal moves away from the coverage area of a WLAN into a 3G cell, a handover to the 3G network is initiated. The handover is triggered under the conditions that (a) RSS average of the WLAN connection falls below a predefined threshold (MOT_{WLAN}), and (b) the estimated lifetime is less than or equal to the handover delay. The mobile terminal continuously calculates the RSS average using the moving average method

$$\overline{RSS}[k] = \frac{1}{W_{av}} \sum_{i=0}^{W_{av}-1} \overline{RSS}[k-i]. \quad (1)$$

Here $\overline{RSS}[k]$ is the calculated average of RSS at time instant k, and W_{av} is the window size, a variable that changes with the velocity of the mobile terminal. Then, the lifetime metric $EL[k]$ is calculated by using $\overline{RSS}[k]$, the RSS change rate $S[k]$, and a parameter called Application Signal Strength Threshold (ASST) as follows:

$$EL[k] = \frac{\overline{RSS}[k] - ASST}{S[k]}. \quad (2)$$

The RSS change rate $S[k]$ varies with the window size of the slope estimator and the RSS sampling interval. For details on calculating $S[k]$, please refer to Eqs. (4)–(6) in [54]. The ASST is an application dependent parameter which represents a composite of the channel bit error rate, application error resilience and application QoS requirements. A look-up table for the optimal ASST values is provided in the paper.

In the second scenario, when the mobile terminal moves towards a WLAN cell, the handover to the WLAN is triggered if the average RSS measurements of the WLAN signal is larger than a threshold ($\mathrm{MIT_{WLAN}}$) and the available bandwidth of the WLAN meets the bandwidth requirements of the application. The flowchart of Zahran et al.'s heuristic is depicted in Fig. 3.

Benefits of Zahran et al.'s algorithm can be summarized as follows. First, by introducing the lifetime metric, the algorithm adapts to the application requirements and the user mobility, reducing the number of superfluous handovers significantly. Second, there is an improvement on the average throughput for the user because of the mobile terminal's ability to remain connected to the WLAN cell as long as possible. However, packet delays grow with an increase in the lifetime, due to the deterioration of the channel condition as the mobile terminal approaches the edge of the WLAN cell. This issue can be critical for delay sensitive applications and degrade their performance. To solve this problem, ASST is tuned according to various system parameters, including delay thresholds, mobile terminal velocities, handover signaling costs and packet delay penalties.

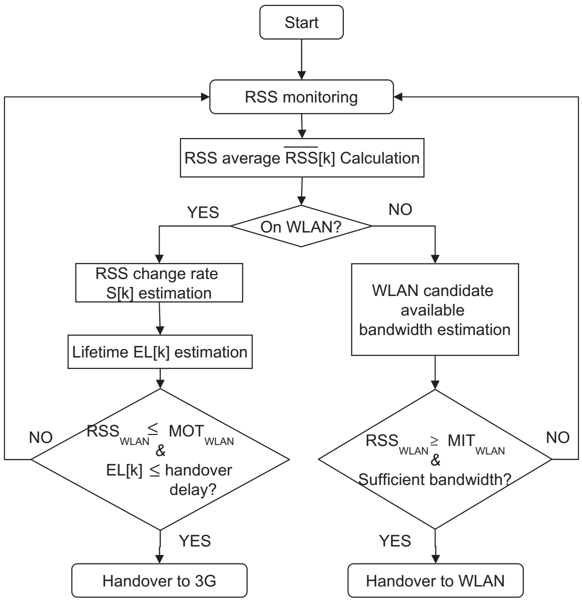

Fig. 3. Zahran et al.'s VHD algorithm [53].

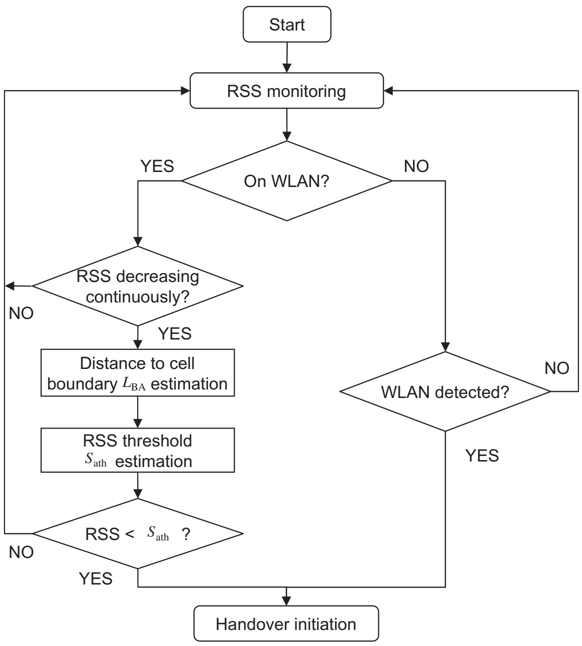

Fig. 4. Mohanty and Akyildiz's VHD heuristic [29].

3.1.2. An RSS threshold based dynamic heuristic

Mohanty and Akyildiz [29] proposed a WLAN to 3G handover decision method based on comparison of the current RSS and a dynamic RSS threshold (S_{dth}) when a mobile terminal is connected to a WLAN access point. S_{dth} (in dBm) is calculated as

$$S_{\mathrm{dth}} = \mathrm{RSS_{min}} + 10\beta \log 10\left(\frac{d}{d - L_{\mathrm{BA}}}\right) + \epsilon, \quad (3)$$

where $\mathrm{RSS_{min}}$ (in dBm) is the minimum level of the RSS required for the mobile terminal to communicate with an access point, β is the path loss coefficient, d is the side length of the WLAN cell (in meters, a WLAN cell is assumed to have a hexagonal shape in this study), L_{BA} is the shortest distance between the point at which handover is initiated and WLAN boundary, and ϵ (in dB) is a zero-mean Gaussian random variable with a standard deviation that represents the statistical variation in RSS caused by shadowing. The distance L_{BA} depends on the desired handover failure probability p_f, the velocity of the mobile terminal v, the WLAN to 3G handover delay τ, and is calculated as

$$L_{\mathrm{BA}} = \left[\tau^2 v^2 + d^2\left(p_f - 2 + 2\sqrt{1 - p_f}\right)\right]^{\frac{1}{2}}. \quad (4)$$

The use of a dynamic RSS threshold helps reducing the incidences of false handover initiation and keeping the handover failures below a limit (the flowchart of the heuristic is shown in Fig. 4.). However, in this algorithm, the handover failure probability from 3G network to a WLAN cell is considered to be zero since the 3G network coverage is assumed to be available all the time, and thus according to the mechanism, a handover to a WLAN is always desirable whenever the mobile terminal enters the WLAN coverage. Yan et al. [48] (discussed in the next section) point out in their study that this is not efficient when the mobile terminal's traveling time inside a WLAN cell is less than the handover delay, and in such cases a handover may result in wastage of network resources.

3.1.3. A traveling distance prediction based heuristic

To eliminate unnecessary handovers in the method presented in Section 3.1.2, Yan et al. [48–50] developed a VHD algorithm that takes into consideration the time the mobile terminal is expected to spend within a WLAN cell. The method relies on the estimation of WLAN traveling time (i.e. time that the mobile terminal is expected to spend within the WLAN cell) and the calculation of a time threshold. A handover to a WLAN is triggered if the WLAN coverage is available and the estimated traveling time inside the WLAN cell is larger than the time threshold. The traveling time (t_{WLAN}) is estimated as

$$t_{\mathrm{WLAN}} = \frac{R^2 - l_{\mathrm{OS}}^2 + v^2(t_s - t_{\mathrm{in}})^2}{v^2(t_s - t_{\mathrm{in}})}, \tag{5}$$

where R is the radius of the WLAN cell, l_{OS} is the distance between the access point and where the mobile terminal takes an RSS sample, v is the velocity of the mobile terminal, and t_s and t_{in} are the times at which the RSS sample is taken and the mobile terminal enters the WLAN cell coverage, respectively. l_{OS} is estimated by using the RSS information and log-distance path loss model.

The time threshold (T_{WLAN}) is calculated based on various network parameters as

$$T_{\mathrm{WLAN}} = \frac{2R}{v} \sin\left(\sin^{-1}\left(\frac{v\tau}{2R}\right) - \frac{\pi}{2}P\right) \tag{6}$$

where τ is the handover delay from cellular network to WLAN and P is the maximum tolerable handover failure, or unnecessary handover probability. A handover to the cellular network is initiated if the WLAN RSS is continuously fading and the mobile terminal reaches a handover commencement boundary area based on the mobile terminal's speed. Fig. 5 shows Yan et al.'s heuristic.

The main advantage of this heuristic is that it minimizes handover failures, unnecessary handovers and connection breakdowns. But the method relies on sampling and averaging RSS points, which introduces increased handover delay. The performance impact of the handover delay should be further discussed and balanced against the probability of unnecessary handovers.

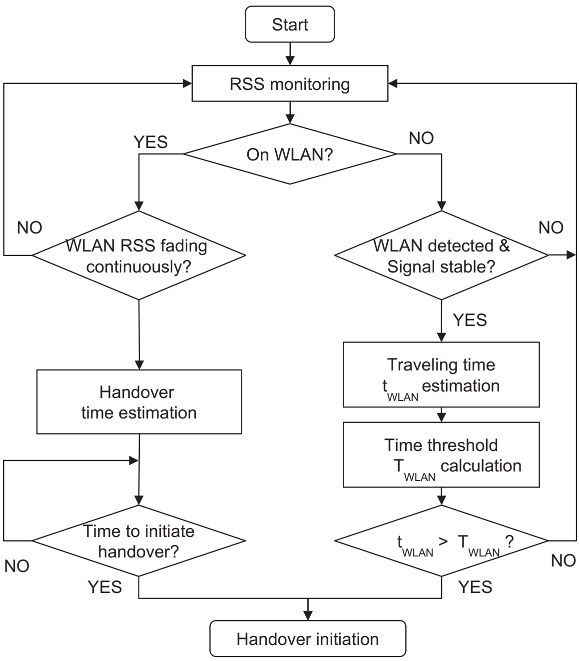

Fig. 5. Yan et al.'s VHD heuristic [49–51].

3.2. Bandwidth based VHD Algorithms

Bandwidth based VHD algorithms consider available bandwidth for a mobile terminal or traffic demand as the main criterion [34,22,51,10]. In this section, three typical bandwidth based VHD algorithms are discussed in detail.

3.2.1. A QoS based heuristic

Lee et al. [22] devised a QoS based VHD algorithm which takes residual bandwidth and user service requirements into account in deciding whether to handover from a WLAN to Wireless Wide Area Network (WWAN) and vice versa.

When the mobile terminal is connected to a WLAN, the handover algorithm is initiated if the measured RSS is consistently below a threshold ($\mathrm{RSS_{T1}}$). The algorithm also takes the state of the mobile terminal into consideration. If the mobile terminal is in the idle state, a handover to the preferred access network is performed, otherwise the handover decision is based upon the user application type. For delay-sensitive applications, a handover occurs only if the current serving WLAN is not able to provide enough bandwidth for the application while the WWAN is able to provide the necessary bandwidth. For delay-tolerant applications, a handover takes place if the WWAN provides higher bandwidth than the WLAN. Approximate value of the residual bandwidth of the WLAN is evaluated by the following formula:

$$\begin{aligned} \mathit{residual\_bandwidth} = \mathit{throughput} \times (1 - \alpha \\ \times \mathit{channel\_utilization}) \\ \times (1 - \mathit{packet\_loss\_rate}), \end{aligned} \tag{7}$$

where *throughput* is the throughput that can be shared among mobile terminals in the WLAN, *channel_utilization* is the percentage of time the access point senses the medium is busy using the carrier sense mechanism, α is a factor that reflects IEEE 802.11 MAC overhead (it is set to 1.25 in [22]), and *packet_loss_rate* is the portion of transmitted medium access control (MAC) protocol data units (MPDUs) that require retransmission, or are discarded as undeliverable. The values of *channel_utilization* and *packet_loss_rate* are obtained from the information in the beacon frame carrying the QoS basic service set (QBSS) load sent by an access point, as defined in IEEE 802.11e [14].

When the mobile terminal is connected to a WWAN, a similar process is carried out if consecutive beacons from the WLAN with RSS above a threshold ($\mathrm{RSS_{T2}}$) are received. The flowchart of Lee et al.'s algorithm is depicted in Fig. 6.

By considering the available bandwidth as the main VHD criterion, this heuristic is able to achieve high system throughput, and by taking application types into account, lower handover latency for delay-sensitive applications is achieved. However, acquiring the available bandwidth information in a cellular network for handover decisions is difficult [22]. Furthermore, in this method, a handover to the preferred network is performed when the mobile terminal is in the idle state. However, when the mobile terminal is staying in the preferred network for only a short

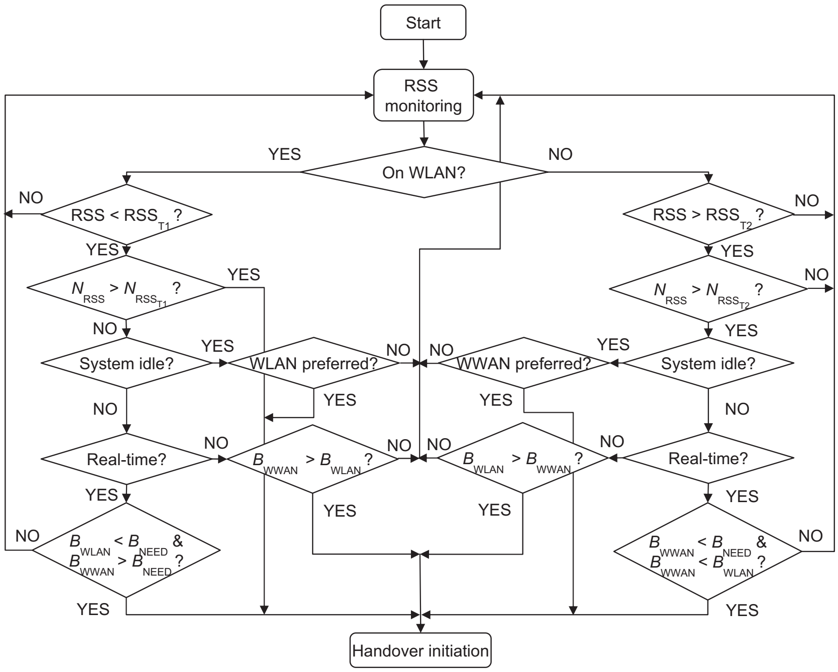

Fig. 6. Lee et al.'s VHD heuristic [22].

period, the movement can result in high blocking rate for new applications.

3.2.2. A signal to interference and noise ratio (SINR) based heuristic

Yang et al. [51] presented a bandwidth based VHD method between WLANs and a Wideband Code Division Multiple Access (WCDMA) network using Signal to Interference and Noise Ratio (SINR). The SINR calculation of the WLAN signals is converted to an equivalent SINR to be compared with the SINR of the WCDMA channel

$$\gamma_{AP} = \Gamma_{AP}\left[\left(1+\frac{\gamma_{BS}}{\Gamma_{BS}}\right)^{\frac{W_{BS}}{W_{AP}}} - 1\right] \tag{8}$$

where γ_{AP} and γ_{BS} are the SINR at the mobile terminal when associated with WLAN and WCDMA, respectively. Γ is the dB gap between the uncoded Quadrature Amplitude Modulation (QAM) and channel capacity, minus the coding gain, and Γ_{AP} equals to 3dB for WLAN and Γ_{BS} equals to 3dB for WLAN, as stated by the authors. W_{AP} and W_{BS} are the carrier bandwidth of WLAN and WCDMA links. A handover to the network with larger SINR is performed, as shown in the flowchart (Fig. 7).

SINR based handovers can provide users higher overall throughput than RSS based handovers since the available throughput is directly dependent on the SINR, and this algorithm results in a balanced load between the WLAN and the WCDMA networks. But such an algorithm may also introduce excessive handovers with the variation of the SINR causing the node to hand over back and forth between two networks, commonly referred to as ping-pong effect [37].

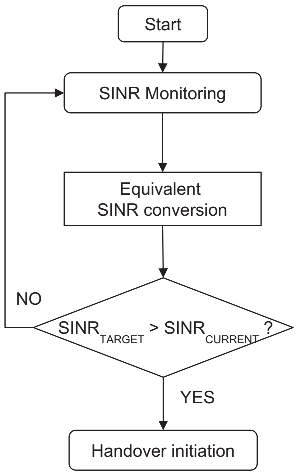

Fig. 7. Yang et al.'s VHD heuristic [48].

3.2.3. A wrong decision probability (WDP) prediction based heuristic

In [10], Chi et al. proposed a VHD heuristic based on the wrong decision probability (WDP) prediction. The WDP is calculated by combining the probability of unnecessary and missing handovers. Assume that there are two networks i and j with overlapping coverage, and b_i and b_j are their available bandwidth. An unnecessary handover occurs when the mobile terminal is in network i and decides to handover to j, but b_j is less than b_i after this decision. A missing handover occurs when the mobile terminal decides to stay connected to network i, but b_i is less than b_j after this decision.

A handover from network i to network j is initiated if $P_r < \rho \times l_0$ or $b_j - b_i \leqslant L$, where P_r is the unnecessary handover probability, ρ is the traffic load of network i, $l_0 = 0.001$, and L is a bandwidth threshold. The flowchart of this algorithm is shown in Fig. 8.

The authors show that this algorithm is able to reduce the WDP and balance the traffic load, however, RSS is not considered. A handover to a target network with high bandwidth but weak received signal is not desirable as it may result in connection breakdown.

A summary of the bandwidth based VHD heuristics is shown in Table 2.

3.3. Cost function based VHD algorithms

The cost function based algorithms combine metrics in a cost function. Many studies have been done in this area [3,8,56,9,23,18,43,40,24]. In this section, we evaluate three representative cost function based VHD algorithms.

3.3.1. A multiservice based heuristic

Zhu and McNair's [56,57] VHD algorithm relies on a cost function which calculates the "cost" of possible target networks. The algorithm prioritizes all the active applications, and then the cost of each possible target network for the service with the highest priority is calculated by

$$C_s^n = \sum W_{s,j}^n Q_{s,j}^n, \quad E_{s,j}^n \neq 0, \tag{9}$$

where C_s^n is the per-service cost for network n, $Q_{s,j}^n$ is the normalized QoS provided by network n for parameter j and service s, $W_{s,j}^n$ is the weight which indicates the impact of the QoS parameter on the user or the network, and $E_{s,j}^n$ is the network elimination factor, indicating whether the minimum requirement of parameter j for service s can be met by network n. The total cost is the sum of the cost of each QoS parameter, including the bandwidth, battery power and delay. The service is handed over to the network with the minimum cost. The flowchart of this algorithm is shown in Fig. 9.

The primary benefits brought by the use of cost function and by independently initiating handovers for different applications are the increased percentage of user satisfied requests and reduced blocking probability. However, the

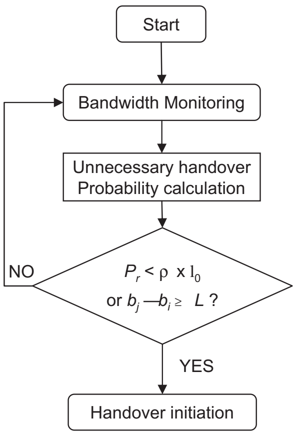

Fig. 8. Chi et al.'s VHD heuristic [10].

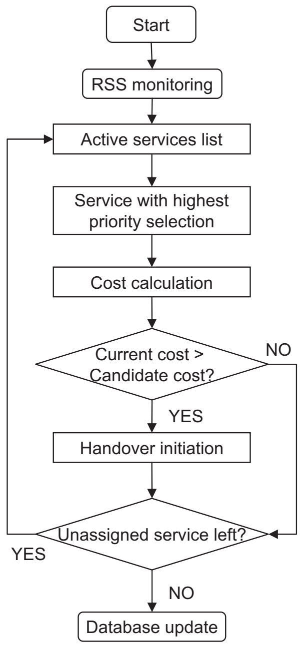

Fig. 9. Zhu and McNair's VHD heuristic [56,57].

Table 2
A summary of bandwidth based VHD algorithms.

Heuristic	Applicable area area	Feature	Advantages	Disadvantages
Lee et al.'s heuristic [22]	Between WWANs and WLANs	The bandwidth is combined with the RSS, system status and application type to make handover decisions	• High system throughput • Low handover latency for real-time transmission	• Difficulty in acquiring available bandwidth information • Increased new application blocking rate
Yang et al.'s heuristic [51]	Between WCDMA and WLANs	The SINR values are compared to determine the handover decision	• High overall throughput • Balance of the network load between WLANs and WCDMA	• Excessive handovers • Ping-pong effect
Chi et al.'s heuristic [10]	Between any two wireless networks	Available bandwidth, network traffic and unnecessary handover probability are considered in the handover decision criteria	• Reduced unnecessary handover probability • Balance of the traffic load	• Increased connection breakdown probability without considering the RSS

authors did not discuss how the QoS factors are normalized or how the weights for the QoS factors are assigned.

3.3.2. A cost function based heuristic with normalization and weights distribution

Similar to Zhu and McNair's method [56,57], Hasswa et al. also proposed a cost function based handover decision algorithm in which the normalization and weights distribution methods are provided [18,32]. A network quality factor is used to evaluate the performance of a handover target candidate as

$$Q_i = \omega_c C_i + \omega_s S_i + \omega_p P_i + \omega_d D_i + \omega_f F_i, \tag{10}$$

where Q_i is the quality factor of network i, C_i, S_i, P_i, D_i and F_i stand for cost of service, security, power consumption, network conditions and network performance, and ω_c, ω_s, ω_p, ω_d and ω_f are the weights for these network parameters. Since each network parameter has a different unit, a normalization procedure is used and the normalized quality factor for network n is calculated as

$$\begin{aligned} Q_i = {} & \frac{\omega_c(1/C_i)}{\max((1/C_1),\ldots,(1/C_n))} + \frac{\omega_s S_i}{\max(S_1,\ldots,S_n)} \\ & + \frac{\omega_p(1/P_i)}{\max((1/P_1),\ldots,(1/P_n))} + \frac{\omega_d D_i}{\max(D_1,\ldots,D_n)} \\ & + \frac{\omega_f F_i}{\max(F_1,\ldots,F_n)}. \end{aligned} \tag{11}$$

A handover necessity estimator is also introduced to avoid unnecessary handovers. Fig. 10 depicts the operation of this algorithm.

High system throughput and user's satisfaction can be achieved by introducing Hasswa's heuristic, however, some of the parameters such as security and interference levels are difficult to estimate, and the authors have yet to provide information on how to measure these parameters.

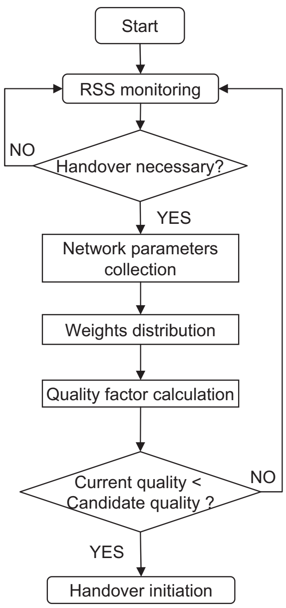

Fig. 10. Hasswa et al.'s VHD heuristic [18,32].

3.3.3. A weighted function based heuristic

Tawil et al. [43] presented a weighted function based VHD algorithm which delegates the VHD calculation to the visited network instead of the mobile terminal. The weighted function of a network candidate is defined as

$$Q_i = W_B B_i + W_{D_P} \frac{1}{D_{P_i}} + W_C \frac{1}{C_i}, \tag{12}$$

where Q_i represents the quality of network i, B_i, D_{P_i} and C_i are bandwidth, dropping probability and monetary cost of service, and W_B, W_{D_P} and W_C are their respective weights where

$$W_B + W_{D_P} + W_C = 1. \tag{13}$$

The network candidate with the highest Q_i is selected as the handover target. The process of this algorithm is shown in Fig. 11.

By assigning the calculation to the visited network, the resource of the mobile terminal can be saved so that the system is able to achieve short handover decision delay, low handover blocking rate and high throughput. However, the method requires extra cooperation between the mobile terminal and the point of attachment of the visited network, which may cause additional latency and excessive load to the network when there is a large number of mobile terminals.

A summary of the cost function based VHD heuristics is shown in Table 3.

3.4. Combination algorithms

Combination algorithms are based on artificial neural networks or fuzzy logic, and combine various parameters in the handover decision such as the ones used in the cost function algorithms. Many combination algorithms have been proposed [6,55,17,19,25,31,35,47]. In the following

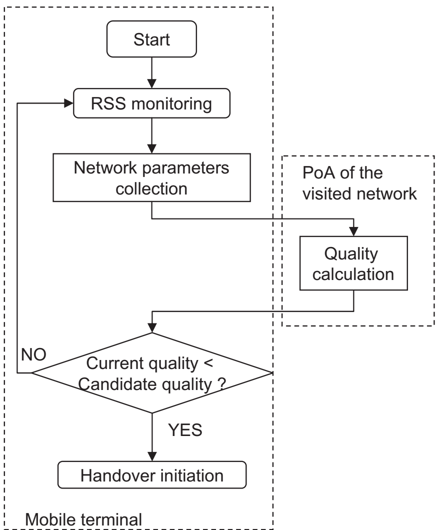

Fig. 11. Tawil et al.'s VHD heuristic [43].

Table 3
A summary of cost function based VHD algorithms.

Heuristic	Applicable area	Feature	Advantages	Disadvantages
Zhu and McNair's heuristic [56]	Between any two heterogeneous wireless networks	• A cost function is introduced and users' active applications are individually handed over to target networks with the minimum costs	• Increased user satisfaction • Low blocking probability	• Missing detailed information such as normalization method and weights assignment to make the algorithm realistic
Hasswa et al.'s heuristic [18]	Between any two heterogeneous wireless networks	• Normalization and weights distribution methods are provided • A handover necessity estimator is proposed	• High throughput • High users' satisfaction	• Difficulty in estimating parameters such as security and interference level
Tawil et al.'s heuristic [43]	Between any two heterogeneous wireless networks	• A weighted function is introduced • The handover calculation is delegated to the visited network instead of the MT	• Short handover delay • Low handover blocking rate • High throughput	• Requirement of cooperation between the MT and the point of attachment of the visited network

sections, we analyze and evaluate three typical combination algorithms.

3.4.1. A multilayer feedforward artificial neural network based heuristic

Nasser et al. developed a VHD algorithm based on artificial neural networks (ANNs) [31]. As shown in Fig. 12, the mobile device collects features of available wireless networks and sends them to a middleware called vertical handover manager through the existing links. These network features are used to help with handover decisions and include network usage cost, security, transmission range and capacity. The vertical handover manager consists of three main components: network handling manager, feature collector and ANN training/selector. A multilayer feedforward ANN is used to determine the best handover target wireless network available to the mobile device, based on the user's preferences.

The topology of the ANN is shown in Fig. 13. It consists of an input layer, a hidden layer and an output layer. The input layer consists of five nodes representing various parameters of the handover target candidate networks. The hidden layer consists of variable number of nodes which are activation functions. The output layer has one node which generates the network ID of the handover target. All the neurons use sigmoid activation function [39].

The authors have adopted the same cost function as in [18], and for ANN training they have generated a series of user preference sets with random weights. Then the system has been trained to select the best network among all the candidates.

The authors report that by properly selecting the learning rate and the acceptable error value, the system was able to find the best available network successfully. However, the algorithm suffers from a long delay during the training process.

3.4.2. A method that uses two neural networks

Pahlavan et al. [35] proposed two neural network based decision methods for horizontal and vertical handovers. Here, we only discuss the vertical handovers mechanism.

In the method for vertical handovers, an ANN is used for handovers from the WLAN to the General Packet Radio Service (GPRS). The ANN, as shown in Fig. 14, consists of an input layer, two middle layers and an output layer. The mobile node performs periodical RSS measurements, and

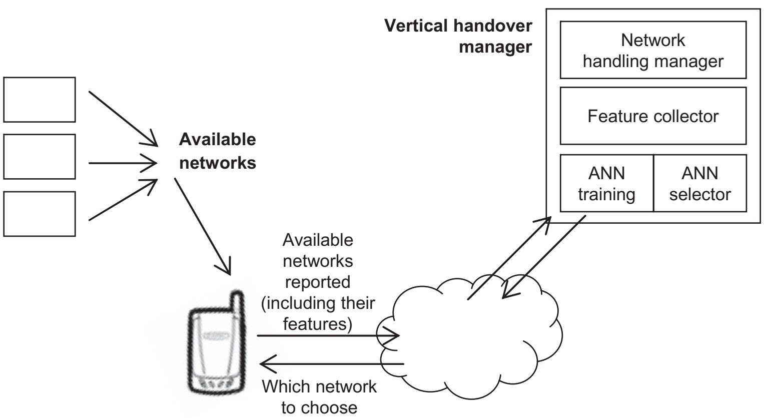

Fig. 12. Architecture of Nasser et al.'s system [31].

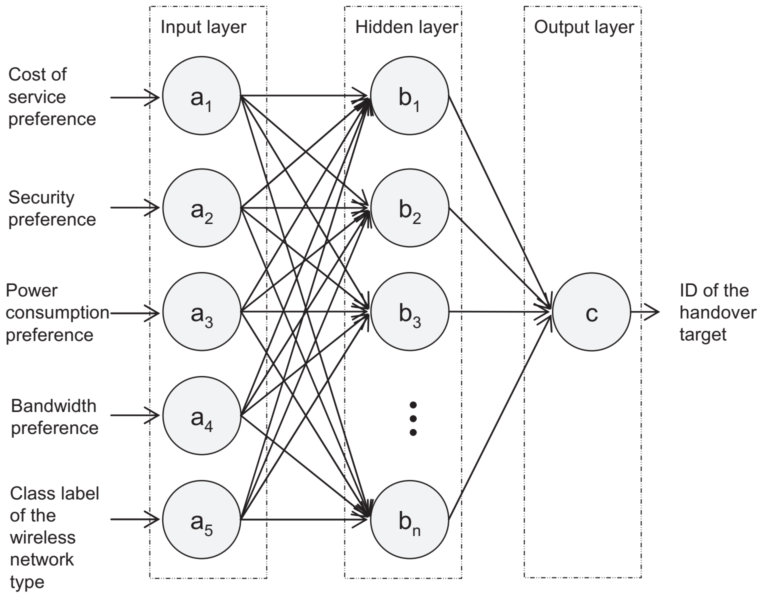

Fig. 13. Topology of the feedforward ANN used in Nasser et al.'s VHD scheme [31].

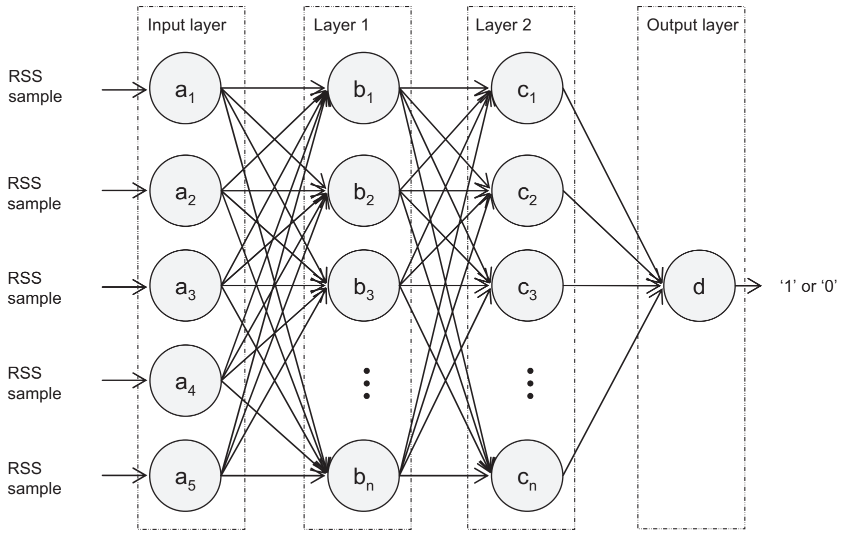

Fig. 14. Structure of the ANN used for vertical handover decisions in Pahlavan et al.'s VHD scheme [35]. RSS measurements are done periodically and most recent five samples are fed into the ANN.

five most recent RSS samples of the access point are fed into the ANN. The output is a binary signal: The value '1' leads to a handover to the GPRS, and the value '0' means that the mobile node should remain connected to the access point.

The ANN is trained before used in the decision process. Training is done by taking a number of RSS samples from the access point and, using a pattern recognition technique, selecting the most suitable network, while minimizing the handover delay and ping-pong effect.

This heuristic can reduce the number of handovers by eliminating the ping-pong effect, but the paper lacks detail on how the neural network is trained and why the particular parameters are selected. This algorithm also has the disadvantage of the increased algorithm complexity and the training process to be performed beforehand.

3.4.3. A fuzzy logic based heuristic

Besides artificial neural networks, fuzzy logic [19,25,47] is also used for creating schemes to deal with a rich set of input parameters for making vertical handover decisions. Xia et al.'s method [47] is a good representative example of this approach. This scheme is used to handle handovers between WLANs and Universal Mobile Telecommunications Systems (UMTS). A pre-decision unit is used in this scheme.

In this algorithm, if the mobile terminal is connected to the WLAN, and the velocity of the mobile terminal (v) is higher than a velocity threshold (v_T), a handover to the UMTS is directly initiated to prevent a connection breakdown. Otherwise, the pre-decision unit checks whether the predicted RSS satisfies its requirements. If the predicted RSS from the WLAN (PR_W) is larger than its threshold (P_{rW}), or the predicted RSS from the UMTS (PR_U) is smaller than its threshold (P_{rU}), no handover is triggered. After the pre-decision, the fuzzy logic based normalized quantitative decision (FNQD) is applied. The FNQD has three procedures: fuzzification, normalization and quantitative decision. The three inputs, current RSS, predicted RSS and bandwidth, are fuzzified and normalized to generate performance evaluation values (PEV), and the VHD is made by comparing PEVs of the network candidates.

If the mobile terminal is connected to the UMTS and the WLAN connectivity is available, the pre-decision unit is used to eliminate unnecessary handovers when the velocity of the mobile terminal is larger than the threshold (v_T). A similar process is executed as the one described in the handover from WLANs to UMTSs. The process of this algorithm is illustrated in Fig. 15.

The heuristic in this study is able to achieve improved performance by reducing the number of unnecessary handovers and avoiding the ping-pong effect. However, when the PEVs are calculated, fixed weights are assigned to the three inputs. This is not practical because the network condition and user requirements vary in different situations. In addition, more performance evaluation criteria such as handover delay and system load need to be addressed.

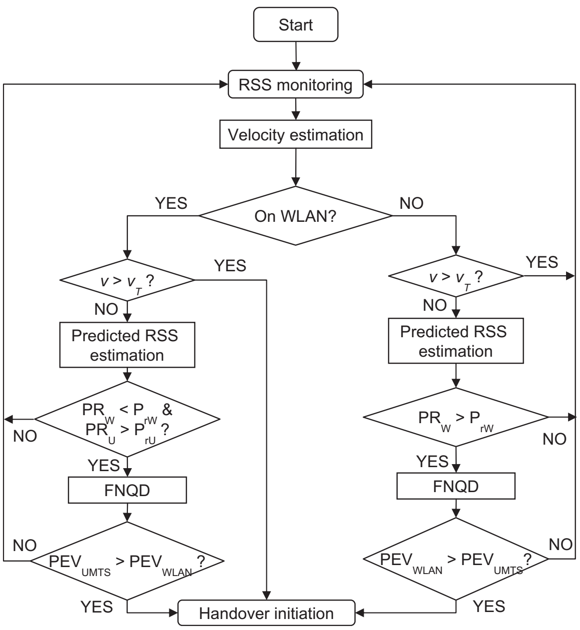

Fig. 15. Xia et al.'s VHD heuristic [47].

A summary of the cost function based VHD heuristics is shown in Table 4.

4. Comparison of the approaches

So far we have discussed twelve VHD algorithms and classified them into four groups based on the criteria they use for making handover decisions. To provide an overall comparison of the four groups, we summarize their features on five aspects: networking technologies that they can be applicable, input parameters, handover target selection criteria, complexity and reliability in Table 5.

The applicable network technologies for RSS based VHD algorithms are usually between macrocellular and microcellular networks, e.g. 3G and WLANs. The algorithms tend to make full usage of WLANs because of their high bandwidth and low cost. The other three types of VHD algorithms can be applied for handovers between a variety of wireless networks.

As for the input parameters, RSS is used as the main input in RSS based VHD algorithms, while the RSS combined with the bandwidth information is usually adopted in bandwidth based VHD algorithms. Various network parameters are used in cost function based or combination algorithms, such as monetary cost, bandwidth, security and power consumption.

For handover target selection criteria, the candidate network with the most stable RSS and highest bandwidth is selected as the handover target in RSS and bandwidth based VHD algorithms, respectively. On the other hand, combination or cost function based algorithms attempt to choose the target network with the highest overall performance. The overall performance is calculated based on the various network parameters.

In terms of complexity, RSS based algorithms are usually the simplest, followed by the bandwidth based algorithms. Cost function based VHD algorithms tend to be more complex as they need to collect and normalize various network parameters, and combination algorithms are the most challenging ones because of their pre-training requirements.

Finally, reliability varies among the algorithms. Fluctuations of RSS decreases the reliability of RSS based VHD algorithms, and the difficulty in measuring available bandwidth reduces the reliability of bandwidth based VHD algorithms. In cost function based algorithms, some parameters such as security level are hard to measure, and they degrade their reliability. As for combination algorithms, since the systems are trained beforehand, they can be considered as the most reliable among the four groups.

For a better understanding of the performance of different VHD algorithms, we provide a quantitative comparison based on the performance metrics mentioned in Section 2.4. Since the authors of each algorithm provide different performance parameters in their studies, direct comparisons are impossible. In Table 6, we provide a summary quantitative comparison based on four performance parameters: delay, number of handovers, handover failure probability and throughput, based on the information provided in the papers. As can be seen, relatively high delays

Table 4
A summary of combination algorithms.

Heuristic	Applicable area	Feature	Advantages	Disadvantages
Nasser et al.'s heuristic [31]	Between any two heterogeneous wireless networks	A cost function is adopted and the system is trained before being used in the handover decision	• High success rate in finding the best network candidate	• Training delay • Increased system complexity
Pahlavan et al.'s heuristic [35]	From WLANs to GPRS	The RSS samples are collected as the inputs of the neural network and the system is trained before being used in the handover decision	• Reduced number of handovers • Elimination of the ping-pong effect	• Lack of detail on training process and parameters selection • Training delay • Increased system complexity
Xia et al.'s heuristic [47]	Between WLANs and cellular networks	Current RSS, predicted RSS and bandwidth are fuzzificated and normalized to be used as the handover decision criteria	• Reduced number of handovers • Elimination of the ping-pong effect	• Fixed weights which fail to meet the need of continuously changing wireless environment

Table 5
A comparative summary of the four groups.

Group	Applicable networking technologies	Input parameters	Handover target selection criteria	Complexity	Reliability
RSS based VHD algorithms	Usually between macrocellular and microcellular networks	RSS as the main input	The network candidate with the most stable RSS	Simple	Reduced reliability because of the fluctuation of RSS
Bandwidth based VHD algorithms	Between any two heterogeneous networks	Bandwidth combined with other parameters such as RSS	The network candidate with the highest bandwidth	Simple	Reduced reliability because of the changing available bandwidth
Cost function based VHD algorithms	Between any two heterogeneous networks	Various parameters such as cost, bandwidth and security	The network candidate with the highest overall performance	Complex	Reduced reliability because of the difficulty in measuring some parameters
Combination algorithms	Between any two heterogeneous networks	Different input parameters depending on different methods	The network candidate with the highest overall performance	Very complex	High reliability because of the training of the system

occur by using RSS based algorithms proposed in [48,54], while the authors in [22,43] argue that their bandwidth and cost function based algorithms are able to maintain shorter handover delays. Combination algorithms suffer from the longest delay among the four groups because of the system complexity. For the case of number of handovers, the use of algorithms in [48,54] lead to reduced number of handovers, the algorithm in [51] introduces excessive handovers because of the variation of SINR, the algorithm in [10] is able to keep the unnecessary handover probability at a low level, and algorithms in [35,47] reduce the number of handovers by eliminating the ping-pong effect. Handover failure probability can always be kept under the desirable value for algorithms in [29,48], while high handover failure probability is observed for the algorithm in [10] without inclusion of RSS. The algorithm in [43] can achieve low failure rate due to its distribution of the decision calculation. As for the throughput, bandwidth and cost function based algorithms are able to achieve higher throughput than RSS based algorithms. Unfortunately the throughput of combination algorithms are not provided by the authors.

In summary, RSS and bandwidth based VHD algorithms are usually simple, but they only consider one or two handover criteria as the inputs and other important parameters such as monetary cost or power consumption level of the networks are ignored. Furthermore, they are usually targeted to only two specific types of network technologies. Cost function based and combination algorithms are more complex, and they take into account wider range of network parameters as compared to others. However, they are mostly in the theoretical analysis stage or still too complex for implementation.

5. Concluding remarks and future research directions

Unfortunately currently proposed VHD algorithms either lack a comprehensive consideration of various network parameters or the studies reporting these algorithms lack enough detail for implementation. Research into vertical handover decision algorithms in heterogeneous networks is still a challenging area. The main difficulty is devising an algorithm which is truly useful in a wide ranging conditions and user preferences. One possible solution would be, given that computational power of handsets improve phenomenally every year, to implement several VHD algorithms in a handset and adopt adaptive methods that

Table 6
A comparative summary of the 12 VHD algorithms presented in this survey.

Groups/ heuristics		Delay	Number of handovers	Handover failure probability	Throughput
RSS based	Zahran et al.'s algorithm [53]	Relatively high packet delay probability (up to 1%) but can be reduced by adjusting ASST	Reduces up to 85% comparing with traditional hysteresis VHD	Not provided	Decreases as the velocity increases; Can provide overall higher throughput (up to 33%) than traditional hysteresis VHD
	Mohanty and Akyildiz's algorithm [29]	Not provided	Not provided	Can be always kept under the desirable value (2%) as the velocity increases	Not provided
	Yan et al.'s algorithm [48]	Extra RSS sampling delay (up to 2 s)	Decreases as the velocity increases; The unnecessary handover probability can be always kept under the desirable value (0.04)	Can be always kept under the desirable value (0.02) as the velocity increases	Not provided
Bandwidth based	Lee et al.'s algorithm [22]	Short handover delay (average 455ms) achieved by considering application types	Not provided	Not provided	Higher throughput (up to 400%) than the traditional method in the handover period
	Yang et al.'s algorithm [51]	Not provided	Excessive handovers can be introduced because the variation of SINR	Not provided	Higher overall throughput (up to 40%) than RSS based handover algorithms
	Chi et al.'s algorithm [10]	Not provided	Small unnecessary handover probability (up to 1.5%)	High handover failure probability without considering RSS	High throughput achieved by balancing the traffic load
Cost function based	Zhu and McNair's algorithm [56]	Not provided	Not provided	Not provided	High overall throughput achieved by spreading users' services over several networks
	Hasswa et al.'s algorithm [18]	Not provided	Not provided	Not provided	Increases by up to 57.9% in different background traffic
	Tawil et al.'s algorithm [43]	Around 50% shorter handover delay compared to centralized VHD	Not provided	Low handover failure rate due to the distribution of the decision calculation	Around 17% higher throughput compared to centralized VHD
Combination algorithms	Nasser et al.'s algorithm [31]	Long handover delay because of the training needed	Not provided	Not provided	Not provided
	Pahlavan et al.'s algorithm [35]	Long delay because of the increased complexity and the training	Reduced number of handovers by eliminating the ping-pong effect	Not provided	Not provided
	Xia et al.'s algorithm [47]	Not provided	Reduced number of handovers by eliminating the ping-pong effect	Not provided	Not provided

choose an algorithm intelligently based on conditions and user preferences.

References

[1] I.F. Akyildiz, J. McNair, J.S.M. Ho, H. Uzunalioglu, W. Wang, Mobility management in next-generation wireless systems, Proceedings of the IEEE 87 (8) (1999) 1347–1384.

[2] I.F. Akyildiz, J. Xie, S. Mohanty, A survey of mobility management in next-generation all-IP-based wireless systems, IEEE Wireless Communications Magazine 11 (4) (2004) 16–28.

[3] S. Balasubramaniam, J. Indulska, Vertical handover supporting pervasive computing in future wireless networks, Computer Communications 27 (8) (2004) 708–719.

[4] F. Barcelo, Performance analysis of handoff resource allocation strategies through the state-dependent rejection scheme, IEEE Transactions on Wireless Communications 3 (3) (2004) 900–909.

[5] G.W. Beakley, Overview of commercial satellite communications, IEEE Transactions on Aerospace and Electronic Systems AES-20 (4) (1984) 455–464.

[6] P.M.L. Chan, R.E. Sheriff, Y.F. Hu, P. Conforto, C. Tocci, Mobility management incorporating fuzzy logic for a heterogeneous IP environment, IEEE Communications Magazine 39 (12) (2001) 42–51.

[7] B.-J. Chang, J.-F. Chen, Cross-layer-based adaptive vertical handoff with predictive RSS in heterogeneous wireless networks, IEEE Transactions on Vehicular Technology 57 (6) (2008) 3679–3692.

[8] L.-J. Chen, T. Sun, B. Chen, V. Rajendran, M. Gerla. A smart decision model for vertical handoff, in: Proceedings of the Fourth International Workshop on Wireless Internet and Reconfigurability (ANWIRE'04), Athens, Greece, May 2004, pp. 653–658.

[9] W.-T. Chen, Y.-Y. Shu, Active application oriented vertical handoff in next-generation wireless networks, in: Proceedings of the 2005 IEEE Wireless Communications and Networking Conference (WCNC'05), New Orleans, Louisiana, March 2005, pp. 1383–1388.

[10] C. Chi, X. Cai, R. Hao, F. Liu. Modeling and analysis of handover algorithms, in: Proceedings of the 2007 IEEE Global Telecommunications Conference (GLOBECOM'07), Washington, DC, USA, November 2007, pp. 4473–4477.

[11] F. Cortes-Rodriguez, D. Munoz-Rodriguez, R. Soto, Position location assisted multi-valued logic handoff algorithm, in: Proceedings of the 50th Vehicular Technology Conference (VTC'99 - Fall), Amsterdam, the Netherlands, September 1999, pp. 775–779.

[12] S. Dekleva, J.P. Shim, U. Varshney, G. Knoerzer, Evolution and emerging issues in mobile wireless networks, Communications of the ACM 50 (6) (2007) 38–43.

[13] D.-J. Deng, H.-C. Yen, Quality-of-Service provisioning system for multimedia transmission in IEEE 802.11 wireless LANs, IEEE Journal on Selected Areas in Communication 23 (6) (2005) 1240–1252.

[14] IEEE802.11 WG Draft Supplement to Part 11. Wireless medium access control (MAC) and physical layer (PHY) specification: medium access control (MAC) enhancements for Quality of Service (QoS). IEEE Standard 802.11e/D4.3, May 2003.

[15] M. Ghaderi, R. Boutaba, Call admission control in mobile cellular networks: a comprehensive survey: research articles, Wireless Communications and Mobile Computing 6 (1) (2006) 69–93.

[16] C. Guo, Z. Guo, Q. Zhang, W. Zhu, A seamless and proactive end-to-end mobility solution for roaming across heterogeneous wireless networks, IEEE Journal on Selected Areas in Communications 22 (5) (2004) 834–848.

[17] Q. Guo, J. Zhu, X. Xu, An adaptive multi-criteria vertical handoff decision algorithm for radio heterogeneous network, in: Proceedings of the 2005 IEEE International Conference on Communications (ICC'05), Seoul, Korea, May 2005, pp. 2769–2773.

[18] A. Hasswa, N. Nasser, H. Hassanein, Tramcar: a context-aware cross-layer architecture for next generation heterogeneous wireless networks, in: Proceedings of the 2006 IEEE International Conference on Communications (ICC'06), Istanbul, Turkey, June 2006, pp. 240–245.

[19] J. Hou, D.C. O'Brien, Vertical handover-decision-making algorithm using fuzzy logic for the integrated radio-and-OW system, IEEE Transactions on Wireless Communications 5 (1) (2006) 176–185.

[20] S.Y. Hui, K.H. Yeung, Challenges in the migration to 4G mobile systems, IEEE Communications Magazine 41 (12) (2003) 54–59.

[21] M. Kassar, B. Kervella, G. Pujolle, An overview of vertical handover decision strategies in heterogeneous wireless networks, Computer Communications 31 (10) (2008) 2607–2620.

[22] C.W. Lee, Li M. Chen, M.C. Chen, Y.S. Sun, A framework of handoffs in wireless overlay networks based on mobile IPv6, IEEE Journal on Selected Areas in Communications 23 (11) (2005) 2118–2128.

[23] D. Lee, Y. Han, J. Hwang, QoS-based vertical handoff decision algorithm in heterogeneous systems, in: Proceedings of the IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'06), Helsinki, Finland, September 2006, pp. 1–5.

[24] S. Lee, K. Sriram, K. Kim, Y.H. Kim, N. Golmie, Vertical handoff decision algorithms for providing optimized performance in heterogeneous wireless networks, IEEE Transactions on Vehicular Technology 58 (2) (2009) 865–881.

[25] H. Liao, L. Tie, Z. Du, A vertical handover decision algorithm based on fuzzy control theory, in: Proceedings of the First International Multi-Symposiums on Computer and Computational Sciences (IMSCCS'06), Hangzhou, China, June 2006, pp. 309–313.

[26] Tsungnan Lin, Chiapin Wang, Po-Chiang Lin, A neural-network-based context-aware handoff algorithm for multimedia computing, ACM Transactions on Multimedia Computing, Communications, and Applications 4 (3) (2008) 1–23.

[27] M. Liu, Z.-C. Li, X.-B. Guo, H.-Y. Lach, Design and evaluation of vertical handoff decision algorithm in heterogeneous wireless networks, in: Proceedings of the 2006 IEEE International Conference on Networks (ICON'06), Singapore, September 2006, pp. 1–6.

[28] J. McNair, F. Zhu, Vertical handoffs in fourth-generation multinetwork environments, IEEE Wireless Communications 11 (3) (2004) 8–15.

[29] S. Mohanty, I.F. Akyildiz, A cross-layer (layer 2 + 3) handoff management protocol for next-generation wireless systems, IEEE Transactions on Mobile Computing 5 (10) (2006) 1347–1360.

[30] W. Mohr, W. Konhauser, Access network evolution beyond third generation mobile communications, IEEE Wireless Communications Magazine 38 (12) (2000) 122–133.

[31] N. Nasser, S. Guizani, E. Al-Masri, Middleware vertical handoff manager: a neural network-based solution, in: Proceedings of the 2007 IEEE International Conference on Communications (ICC'07), Glasgow, Scotland, June 2007, pp. 5671–5676.

[32] N. Nasser, A. Hasswa, H. Hassanein, Handoffs in fourth generation heterogeneous networks, IEEE Communications Magazine 44 (10) (2006) 96–103.

[33] Q.-T. Nguyen-Vuong, N. Agoulmine, Y. Ghamri-Doudane, Terminal-controlled mobility management in heterogeneous wireless networks, IEEE Communications Magazine 45 (4) (2007) 122–129.

[34] J. Nie, J. Wen, Q. Dong, Z. Zhou, A seamless handoff in IEEE 802.16a and IEEE 802.11n hybrid networks, in: Proceedings of the 2005 International Conference on Communications, Circuits and Systems (ICCCAS'05), Hong Kong, China, May 2005, pp. 383–387.

[35] K. Pahlavan, P. Krishnamurthy, A. Hatami, M. Ylianttila, J.P. Makela, R. Pichna, J. Vallstron, Handoff in hybrid mobile data networks, IEEE Personal Communications 7 (2) (2000) 34–47.

[36] H.S. Park, H.S. Yoon, T.H. Kim, J.S. Park, M.S. Duo, J.Y. Lee, Vertical handoff procedure and algorithm between IEEE802.11 WLAN and CDMA cellular network, Mobile Communications (2003) 103–112.

[37] G.P. Pollini, Trends in handover design, IEEE Communications Magazine 34 (3) (1996) 82–90.

[38] K. Sairam, N. Gunasekaran, S.R. Redd, Bluetooth in wireless communication, IEEE Communications Magazine 40 (6) (2002) 90–96.

[39] E. Soria-Olivas, J.D. Martin-Guerrero, G. Camps-Valls, A.J. Serrano-Lopez, J. Calpe-Maravilla, L. Gomez-Chova, A low-complexity fuzzy activation function for artificial neural networks, IEEE Transactions on Neural Networks 14 (6) (2003) 1576–1579.

[40] E. Stevens-Navarro, Y. Lin, V.W.S. Wong, An MDP-based vertical handoff decision algorithm for heterogeneous wireless networks, IEEE Transactions on Vehicular Technology 57 (2) (2008) 1243–1254.

[41] E. Stevens-Navarro, V.W.S. Wong, Comparison between vertical handoff decision algorithms for heterogeneous wireless networks, in: Proceedings of the 63rd Vehicular Technology Conference (VTC'06 – Spring), Melbourne, Australia, May 2006, pp. 947–951.

[42] K. Taniuchi, Y. Ohba, V. Fajardo, S. Das, M. Tauil, Y.-H. Cheng, A. Dutta, D. Baker, M. Yajnik, D. Famolari, IEEE 802.21: media independent handover: features, applicability, and realization, IEEE Communications Magazine 47 (1) (2009) 112–120.

[43] R. Tawil, G. Pujolle, O. Salazar, A vertical handoff decision scheme in heterogeneous wireless systems, in: Proceedings of the 67th Vehicular Technology Conference (VTC'08 – Spring), Marina Bay, Singapore, April 2008, pp. 2626–2630.

[44] U. Varshney, R. Jain, Issues in emerging 4G wireless networks, Computer 34 (6) (2001) 94–96.
[45] F. Wang, A. Ghosh, C. Sankaran, P.J. Fleming, F. Hsieh, S.J. Benes, Mobile wimax systems: performance and evolution, IEEE Communications Magazine 46 (10) (2008) 41–49.
[46] A.E. Xhafa, O.K. Tonguz, Dynamic priority queueing of handover calls in wireless networks: an analytical framework, IEEE Journal on Selected Areas in Communications 22 (5) (2004) 904–916.
[47] L. Xia, L.-G. Jiang, C. He, A novel fuzzy logic vertical handoff algorithm with aid of differential prediction and pre-decision method, in: Proceedings of the 2007 IEEE International Conference on Communications (ICC'07), Glasgow, Scotland, June 2007, pp. 5665–5670.
[48] X. Yan, N. Mani, Y.A. Şekercioğlu, A traveling distance prediction based method to minimize unnecessary handovers from cellular networks to WLANs, IEEE Communications Letters 12 (1) (2008) 14–16.
[49] X. Yan, Y.A. Şekercioğlu, N. Mani, A method for minimizing unnecessary handovers in heterogeneous wireless networks, in: Proceedings of the 2008 International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM'08), Newport Beach, CA, USA, June 2008, pp. 1–5.
[50] X. Yan, Y.A. Şekercioğlu, S. Narayanan, A probability based triggering time estimation method for handover optimization, in preparation.
[51] K. Yang, I. Gondal, B. Qiu, L.S. Dooley, Combined SINR based vertical handoff algorithm for next generation heterogeneous wireless networks, in: Proceedings of the 2007 IEEE Global Telecommunications Conference (GLOBECOM'07), Washington, DC, USA, November 2007, pp. 4483–4487.
[52] T. Zahariadis, D. Kazakos, (R)evolution toward 4G mobile communication systems, IEEE Wireless Communications 10 (4) (2003) 6–7.
[53] A.H. Zahran, B. Liang, Performance evaluation framework for vertical handoff algorithms in heterogeneous networks, in: Proceedings of the 2005 IEEE International Conference on Communications (ICC'05), Seoul, Korea, May 2005, pp. 173–178.
[54] A.H. Zahran, B. Liang, A. Saleh, Signal threshold adaptation for vertical handoff in heterogeneous wireless networks, Mobile Networks and Applications 11 (4) (2006) 625–640.
[55] W. Zhang, Handover decision using fuzzy MADM in heterogeneous networks, in: Proceedings of the 2004 IEEE Wireless Communications and Networking Conference (WCNC'04), Atlanta, Georgia, USA, March 2004, pp. 653–658.
[56] F. Zhu, J. McNair, Optimizations for vertical handoff decision algorithms, in: Proceedings of the 2004 IEEE Wireless Communications and Networking Conference (WCNC'04), Atlanta, Georgia, USA, March 2004, pp. 867–872.
[57] F. Zhu, J. McNair, Multiservice vertical handoff decision algorithms, EURASIP Journal on Wireless Communications and Networking 2006 (2) (2006) 52.

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