



ORIGINAL ARTICLE

# A comprehensive approach to vertical handoff in heterogeneous wireless networks

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**Abstract** A multi-criteria vertical handoff system sensitive to various mobile-terminals' mobility parameters including distance and velocity in a heterogeneous wireless network is analytically formulated and validated via simulations. It is targeted to estimate the essential handoff parameters including outage probability, residual capacity, and signal to interference and noise threshold as well as network access cost. In order to avoid the ping-pong effect in handoff, a signal evolution prediction system is formulated and its performance is examined. Moreover, the handoff scheme is triggered using an on line handoff-initiation-time estimation scheme. When initiated, the handoff procedure begins with a network scoring system based on multi-attribute strategy which results in selection of potentially promising network parameters. Simulation results are shown to track well the analytical formulations.

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## 1. Introduction

For seamless wireless communications, integration of wireless local area network (WLAN) and third generation (3G) cellular networks (CN), should be developed, in order to achieve the targeted next generation wireless networks (NGWN). These wireless access networks (WANs) are combined to provide a ubiquitous environment of wireless access for terminals equipped with multiple network interfaces (see Fig. 1). When mobile terminals (MT) transfer from one network to another, the quality of service (QoS) offered by the network could decrease under certain predefined level. This transfer mechanism

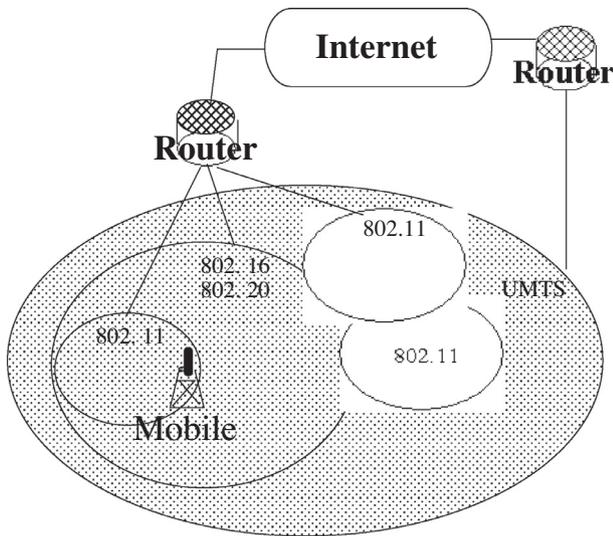
is known as vertical handoff (VHO). A great deal of, previous, studies on VHO are based on received signal strength (RSS), in which handoff decisions are made by comparing the received RSS with a preset threshold values (Benmimoune and Kadoch, 2010; Ahmavaara et al., 2006; Lott et al., 2006). Since RSS based VHO is not a QoS aware scheme, it cannot provide better QoS to user to support multimedia services (Han et al., 2009; Nasser et al., 2006; Rouil et al., 2010). However, as the achievable data rate of a MT is a function of received signal to interference and noise ratio (SINR). Therefore, a SINR based VHO is not expected to achieve maximum throughputs and minimum dropping probabilities only, but also, it is expected to provide a unified radio resource management for the heterogeneous wireless networks (Khadivi et al., 2006).

## 2. Literature survey

Vertical Handover (McNair and Zhu, 2004), is a mechanism in which user maintains connection when switched from one

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**Figure 1** Heterogeneous network overlay.

WAN to another WAN technology (e.g., from WLAN to UMTS and vice versa (see Fig. 1). In IEEE, 2005; Lee et al., 2009, VHO is different from conventional horizontal handover where the MT moves from one base station to another within the same network. In VHO, a session is seamlessly handed over to a new WAN in an interoperable region based on a criterion which evaluates the signal quality. The handover management procedures remain a widely studied issue in the case of heterogeneous network environment. In (Patowary, 2010), MTs should be able to move among these heterogeneous networks in a seamless manner. Various activities of working groups are currently under way such as IEEE 802.21 (I. 802.21, 2006), IETF MIP (Perkins, 2002), or 3GPP standards (3GPP, 2007). IEEE 802.21 supports a mobile-controlled handover (MCHO) scheme and MIP as its mobility management protocol. The details of network selection entity and the specification of handover policies that control handovers are outside the scope of the 802.21.

The objective of a VHO strategy is to guarantee QoS for a variety of applications. In general, the strategy can perform a complex decision criterion that combines large number of (QoS) metrics. The first VHO decision scheme, that considered multiple criteria policies, was proposed by Wang et al. (1999). It introduced a cost function to select the best available WAN based on three policy parameters (bandwidth, power consumption, and cost). Reference (Zhu and McNair, 2006) proposed also a multiservice VHO decision algorithm based on cost function. However, for more efficiency and taking into account more criteria, context-aware decision solution has inspired the authors in Ahmed et al. (2006), Hasswa et al. (2006), Balasubramaniam and Indulska (2004). In Hasswa et al. (2006), Saaty (1990), the authors designed a cross-layer architecture providing context-awareness, smart handover, and mobility control in a W-WAN to WLAN environment. They proposed a VHO decision, with a cost function-based solution, taking into account network characteristics and higher level parameters from transport and application layers. References (Ahmed et al., 2006; Balasubramaniam and Indulska, 2004; Xu et al., 2010) are based on a multiple criteria decision-making algorithm, analytic hierarchy process (AHP). A more advanced

multiple criteria decision algorithms are presented in Chan et al. (2001, 2002), wherein the authors applied the concept of fuzzy logic (FL). They employ decision criteria such as user preferences, link quality, cost, or QoS. Upon literature review, mobility prediction schemes in handoff procedure were found to be very critical in the handoff performance. The handoff procedure is typically based on the received RSS from the base station. There exist several models, schemes and algorithms for handoff procedure which is based on the RSS values as proposed in Chiu and Bassiouini (2000), Pollini (1996), Liu et al. (2008), Taniuchi et al. (2009). These published methods are regularly based on hysteresis and threshold methods.

In this paper, we propose a comprehensive methodology for mobility-prediction based VHO scheme. In this respect, the proposed VHO algorithm considers the received SINR as its handoff criterion. Moreover, the handover process is split into number of phases: handover initiation decision which involves the decision to which point of attachment to execute the handover and its timing. Next is the radio link transfer, which is the task of establishing links to the new point of attachment. This phase is based on the estimates of a number of significant QoS metrics that are seen to satisfy the basic requirements of a variety of applications. This paper is organized as follows; Section 3 outlines the SINR based VHO strategy. Section 4, presents a signal prediction model to predict future SINR evolution and enhances the handoff process. In Section 5, a set of QoS parameters necessary for handover is analytically formulated. Section 6, presents a network selection scheme with examples to validate its performance in Wi Fi, Wi MAX and UMTS networks. The research work carried out in this paper is concluded in Section 7.

### 3. SINR-based vertical handoff strategy

In order to provide guaranteed QoS, the VHO algorithm must be QoS aware. Traditional received signal strength (RSS) based vertical handoff algorithm cannot achieve this (Yang et al., 2007; Xiaohuan et al., 2010). Therefore, we have considered the SINR as handoff criteria similar to that proposed in Xu et al. (2010). A SINR based vertical handoff technique, according to Shannon's capacity formula, states that, the maximum achievable data rate  $R_{AP}$  from WLAN (Access point, AP) and,  $R_{BS}$  from WCDMA (Base station, BS) can be represented by the receiving SINR:  $\gamma_{AP}$  and  $\gamma_{BS}$ .

$$R_{AP} = W_{AP} \log_2 \left( 1 + \frac{\gamma_{AP}}{\Gamma_{AP}} \right) \quad (1)$$

$$R_{BS} = W_{BS} \log_2 \left( 1 + \frac{\gamma_{BS}}{\Gamma_{BS}} \right) \quad (2)$$

where  $W_{AP} = 22$  MHz Krishnamurthy et al. (2006), and  $W_{BS} = 5$  MHz Zahran and Liang (2005) are carrier bandwidths of WLAN and WCDMA,  $\Gamma_{AP} = 3$  dB (Kim et al., 2010) and  $\Gamma_{BS} = 12$  dB (Krishnamurthy et al., 2006) are channel coding loss factors. Since, the data rates of both the networks are different, therefore to compare the SINR of the two networks, the SINR from the source network must be converted into the SINR of the destination. Thus, assuming that the data rates  $R_{AP}$ , and  $R_{BS}$  are equal, the relationship between the SINR of WCDMA and Wi-Fi can be obtained as given below:

$$\gamma_{BS} = \Gamma_{BS} \left( \left( 1 + \frac{\gamma_{AP}}{\Gamma_{AP}} \right)^{\frac{w_{AP}}{w_{BS}}} - 1 \right) \quad (3)$$

The relationship in (3) makes the SINR based VHO method applicable, in which the receiving SINR from WCDMA is being converted to the equivalent,  $\gamma_{AP}$  required to achieve the same data rate in WLAN, and compared with the actual receiving SINR from WLAN. Handoff is triggered when the user receives higher equivalent SINR from another access network. This gives the vertical handoff mechanism the ability to make handoff decision based on specific multimedia QoS requirements such as maximum downlink throughput and minimum probability of (HO) dropping.

#### 4. SINR prediction scheme for heterogeneous wireless networks

As previously mentioned, the achievable data rate of MT is a function of received SINR, which is proportional to the distance between access point (AP) (or (BS)) to the mobile user and to its current interference level. A significant characteristic of the SINR is its high fluctuations caused by user speed as well as the effect of fading, shadowing attenuations. Such variations could cause some unnecessary handoffs especially at cell boundaries, a phenomenon referred to as ping-pong effect. In the rest of this paper we present a SINR evolution-prediction model that is to be adopted. The main task of the prediction system is to extract realistic governing laws of the SINR using available SINR measurements. This process is known as the generation of the grey sequence (Cao, 2003; Deng, 1982; Wen and Huang, 2004; Kayacan et al., 2010). In grey models, the future values of a time series are predicted based only on a set of the most recent measurements depending on the window size of the predictor. Consider the following time sequence of measurements,

$$X^0 = X^0(1), X^0(2), \dots, X^0(n), n \geq 4 \quad (4)$$

where  $X^0$ , is a non-negative sequence and  $n$  is the sample window size of the received data. To obtain the predicted value of the data at time  $(k + 1)$ , the following formula is used, (see Appendix for details),

$$X_p^0(k + 1) = \left( X^0(1) - \frac{b}{a} \right) e^{-ak} (1 - e^a) \quad (5)$$

and the predicted value of data at a future time instant  $(k + H)$ ,

$$X_p^0(k + H) = \left( X^0(1) - \frac{b}{a} \right) e^{-a(k+H-1)} (1 - e^a) \quad (6)$$

To demonstrate the efficiency of the proposed SINR prediction model, the actual value  $X^0$  and the forecasted value  $X_p^0(k + H)$  are compared in the following subsection.

##### 4.1. Preliminary simulations: parameters and modeling

The simulation study is underpinned by a series of assumptions that we shall now describe. A WLAN simulation model is developed (see Fig. 1). In this model, MTs move from one cell to another with varying speeds. The received signals from the base stations are affected by two major factors: path loss and shadow fading.

$$L_{dB} = PL + 10n \log(d) + S \quad (7)$$

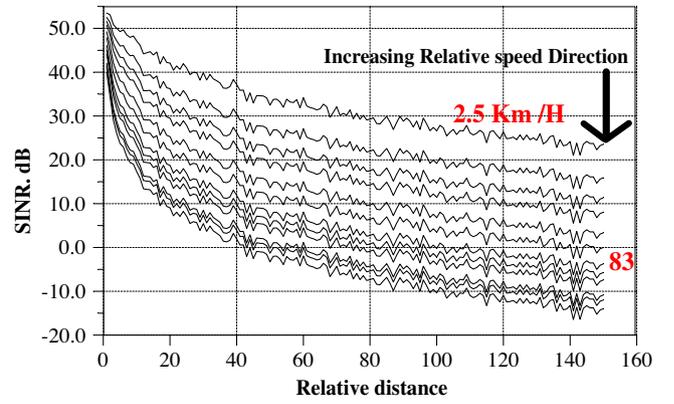


Figure 2 Effect of mobile (relative) speed on SINR.

where PL is the constant power loss,  $n$  is the path loss exponent with values between 2 to 4,  $d$  represents the distance between the MT and WLAN's AP and  $S$ , represents shadow fading which is modeled as Gaussian with mean  $\mu = 0$  and standard deviation  $\sigma$  with values between 6 and 12 dB depending on the environment (Zahram et al., 2006).

##### 4.2. Simulation results

The SINR received from AP is calculated at different mobile speeds and is shown in Fig. 2. In the simulation model, mobile speeds are controlled using two parameters:  $\Delta x$  and  $\Delta t$  representing, respectively, the difference of distances,  $\Delta x$ , travelled during fixed time intervals  $\Delta t$ . Fig. 2, shows the relationship between SINR and the "relative" (simulation) mobile speeds across the WLAN coverage area for speeds ranging from 1 to 100 km/h.

Of importance here to mention that, in real life systems, a "calibration" based formula should, initially, be defined via a set of "practical" experiments in order to quantify the real life relationship between the SINR measurements and the actual mobile speeds in real wireless networks.

Basically, the mobile node measures SINR periodically every  $\Delta t$ -seconds, the evolution of SINR can, then, be translated into the evolution of the "relative" distance between mobile nodes and their base stations as well as their speeds.

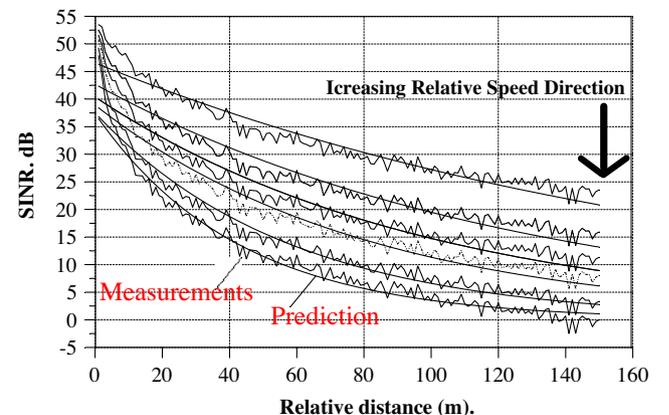


Figure 3 SINR prediction.

As can be seen (Fig. 2), SINR is significantly sensitive to mobility of the users in terms of their distances and speeds. Moreover, an evident characteristic of the SINR is its significant fluctuations caused by fading and shadowing as well as by the speeds of MTs.

Fig. 3, compares the actual values of received SINR and the corresponding prediction values. The simulation results show that the grey model tracks well the evolution of the measured SINR data over a speed range of 1:100 km/H. A desirable feature of the prediction results is that it reveals the exact trends of the current SINR measurements.

### 5. A multiple metric handoff scheme for heterogeneous wireless networks

This section presents different parameters that are seen to be necessary and sufficient for mobility management in VHO systems. The objective is to provide the proper information required to offer a seamless handover services for the end users. First, we show how to decide and when to perform VHO. Second, the results of the proposed VHO protocol are presented. The two phases are implemented via simulation models including 802.11, 802.16 and UMTS technologies developed for this purpose.

#### 5.1. Vertical handoff triggering-time estimation model

In a heterogeneous network environment, the ping-pong effect occurs if the VHO decision parameters are changing rapidly (see Fig. 2), and MT performs handover as soon as it detects the better AP/BS (Lee et al., 2009). A dwell timer scheme has been used to avoid such ping-pong effect (Ylianttila et al., 2001; Hsieh et al., 2003). It starts to work when the vertical handover condition is first satisfied. If the VHO condition persists during the dwell time, the MT performs vertical handover to the target BS/AP after the dwell timer is expired. Otherwise, the MT resets the dwell timer (Ye et al., 2002). Consequently, the MT does not execute premature vertical handover until the target BS/AP becomes stable. However, ping-pong effect can occur if the speed of the MT is relatively high or its moving direction is irregular.

In this paper, we propose a disconnection (breaking)-time estimation scheme wherein an estimate for the mobile's speed,  $\tilde{V} = \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t}$ , is obtained, with  $\Delta x$  and  $\Delta t$  designate the differences of distances travelled and time intervals respectively. Then an estimate of the disconnection time is calculated. Basically, the MT measures SINR periodically every  $n$  second(s). With the prediction model (Section 4) integrated in the present (VHO timing) model, the SINR variations are smoothed out. Then, the evolution of SINR is translated into the evolution of the relative distance between MT and the base station, hence, the relative speed and disconnection time are estimated as follow,

$$\text{Since } \text{SINR (dB)} = A - B * \log_{10}(\text{distance}) \quad (8)$$

with the coefficients  $A$  and  $B$  vary according to the frequency of source emitting signal, therefore, the estimated MT speed,  $V$ , is given by,

$$V = \left( 10^{\frac{K-\text{SINR}(i)}{B}} - 10^{\frac{K-\text{SINR}(i-1)}{B}} \right) / n \quad (9)$$

where, the numerator signifies the distance  $\Delta x$  traveled, and the denominator measures the time interval  $n\Delta t$  with  $\Delta t$  is fixed. On

the other hand,  $\text{SNR}(i)$  is the current measurement and  $\text{SNR}(i-1)$  is the previous one. Clearly,  $V > 0$ , means the MT is moving away from the AP,  $V < 0$  indicates that the MT is moving toward the AP. Note that, this equivalent speed does not represent the real speed of the mobile node. Once again, a calibration formula should be used to match the measurements with real life situations. Now, from Shannon's capacity formula, we can define SINR threshold as the critical threshold under which wireless communications cannot be supported anymore,

$$\gamma_{\text{thr}} = \text{SINR}_{\text{thr}} = \Gamma_{\text{AP}} \left( 2^{\frac{R}{W}} - 1 \right) \quad (10)$$

Then, we can estimate the relative time ( $T_{\text{Break}}$ ) when the mobile node will get disconnected according to its current relative position and positive speed estimate as follows,

$$T_{\text{Break}} = \frac{\left( 10^{\frac{K-\text{SINR}_{\text{thr}}}{B}} - 10^{\frac{K-\text{SINR}(i)}{B}} \right)}{T} \quad (11)$$

From Eqs. (9) and (11), we have,

$$T_{\text{Break}} = n * \frac{\left( 10^{\frac{K-\text{SINR}_{\text{thr}}}{B}} - 10^{\frac{K-\text{SINR}(i)}{B}} \right)}{\left( 10^{\frac{\text{SINR}(i)}{B}} - 10^{\frac{K-\text{SINR}(i-1)}{B}} \right)} \quad (12)$$

Eq. (12) allows estimating the future signal variation and, hence, the MT's mobility evolution. As such, it can deduce as when the MT is about to migrate out of the current wireless coverage. Based on the prediction, the MT is, therefore, able to decide on triggering the VHO procedures but at the right time.

Fig. 4, shows the simulation results for the disconnection-time estimation technique (Eq. (12)). As can be seen, due to estimate fluctuations, it is relatively difficult to decide on the exact time to trigger the handoff procedure. This is where the prediction scheme comes into play in order to define a more accurate VHO timing. Fig. 5, depicts the results of using the prediction scheme presented in Section 4. As can be seen, knowing the "cross-over time", the MT can decide on 'triggering' (initializing) the handoff procedure so that it avoids unnecessary handoffs caused by the significant uncertainties seen in Fig. 4.

#### 5.2. Outage probability estimation model

In wireless environment, network throughput should be kept above a target value and, therefore, packet delay can also be

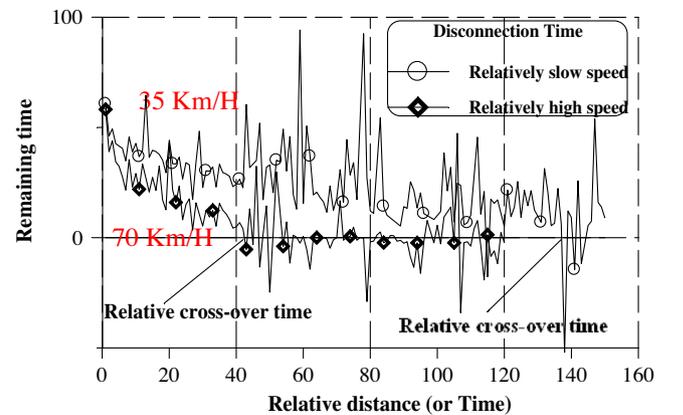


Figure 4 Effect of mobility speed on breaking time.

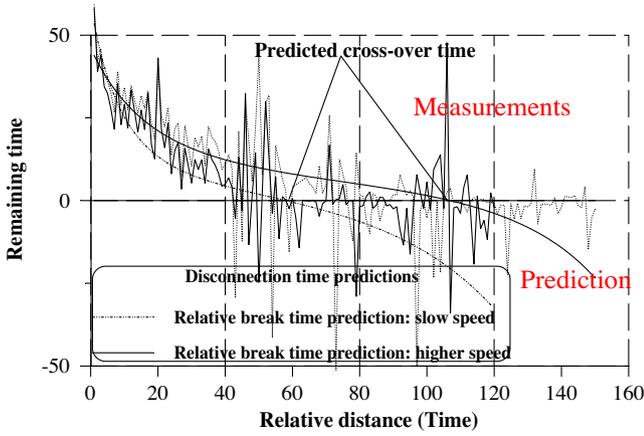


Figure 5 Breaking time prediction.

kept below a target value for a certain application class. This has been, traditionally, characterized by the SINR values. However, guaranteeing SINRs of all applications at all time instances may result in low network utilization especially for bursty traffic. Therefore, in this paper, besides the SINR, we use another QoS metric, namely, the SINR-outage probability. That is, instead of guaranteeing the SINR all the time, we can guarantee that the SINR outage probability is below some target value. In the following we derive the SINR outage probability.

In general, the propagation attenuation for a user at a distance  $r$  from the base station is modeled (Nkansah-Gyekye and Agbinya, xxxx) as,

$$\alpha(r, \xi) = r^\mu 10^{\xi/10}, \quad (13)$$

where  $\mu$  is the exponent of the distance and  $\xi$  is the dB attenuation due to log-normal shadowing with zero mean and standard deviation  $\sigma$ . Suppose that we impose the requirement that the link achieves at least the performance of un-shadowed propagation for all but a fraction,  $P_{\text{out}}$ , of the time which is denoted the outage probability. This means that the desired performance will be achieved whenever the shadowing attenuation  $\xi \leq \gamma$  where  $\gamma$  here designates the SINR. Hence, the outage probability, or the fraction of time wherein the performance is not achieved is,

$$P_{\text{out}} = \Pr(\xi > \gamma) = \frac{1}{\sqrt{2\pi}} \int_{\gamma}^{\infty} e^{-\frac{\xi^2}{2\sigma^2}} d\xi$$

$$= Q\left(\frac{\gamma}{\sigma}\right) \quad (14)$$

where  $Q(\cdot)$  designates the complement Gaussian error function. Fig. 6, shows the simulation results of the outage probability at different locations and speeds within the coverage area of 802.11 network. The prediction mechanism (Section 4) is, again, integrated within the outage probability estimation model in order to smooth out the probability results. As can be seen, the outage probability estimate shows a desirable sensitivity to mobile's speed as well as its relative location in the coverage area of the AP. This reveals the fact that our estimation scheme will play a significant role in making efficient handoff decision as will be seen later.

### 5.3. Residual capacity estimation model

In VHO, users seek for maximum available bandwidth from the integrated heterogeneous networks especially for multimedia service applications. In this paper, MT keeps measuring received SINR for Wi Fi, Wi MAX and UMTS, conducting the  $\gamma_{\text{AP}}$ ,  $\gamma_{\text{BS}}$  and  $\gamma_{\text{MAX}}$  conversions (Section 3). The handoff strategy (next section), allocates users with low bandwidth requirements to networks optimized for a particular data rate and service provisioning and, hence, leaves high speed connections free for users requiring rather high QoSs. In (Wang et al., 2003), the concept of residual capacity was introduced, defined as the additional number of calls a base station can accept such that the system wide outage probability will be guaranteed to remain below a certain level. The residual capacity is dynamically updated at each cell according to the SINR measurements. The residual capacity is defined as follows,

$$C_{\text{rsd}} \left[ \frac{1}{\text{SINR}_{\text{thr}}} - \frac{1}{\text{SINR}_k} \right] \quad (15)$$

where  $\text{SINR}_{\text{thr}}$  and  $\text{SINR}_k$  are, respectively, the minimum SINR required to support the service rate and the actual SINR received. It is envisaged that a SINR-based  $C_{\text{rsd}}$  will play an important role in the handoff strategy proposed in this paper.

Fig. 7, depicts the simulation/prediction results for the residual capacity estimation scheme. Here, the estimator/predictor obtains the  $C_{\text{rsd}}$  estimates of all neighboring, potential,

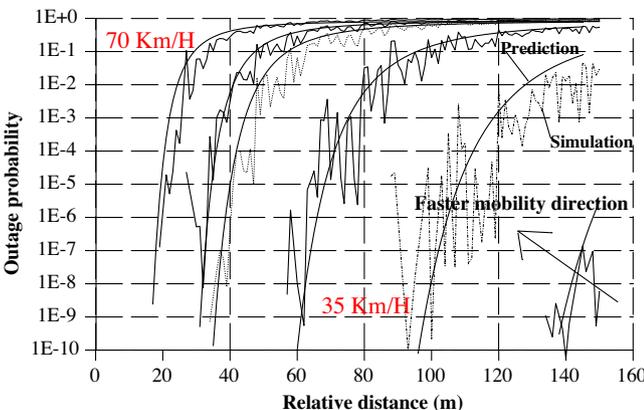


Figure 6 Outage probability prediction.

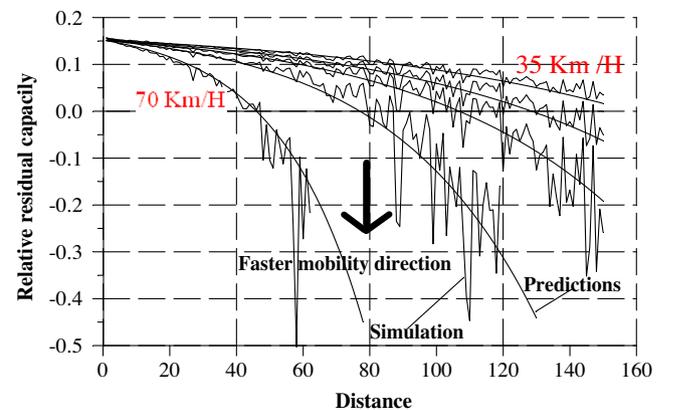


Figure 7 Residual capacity prediction.

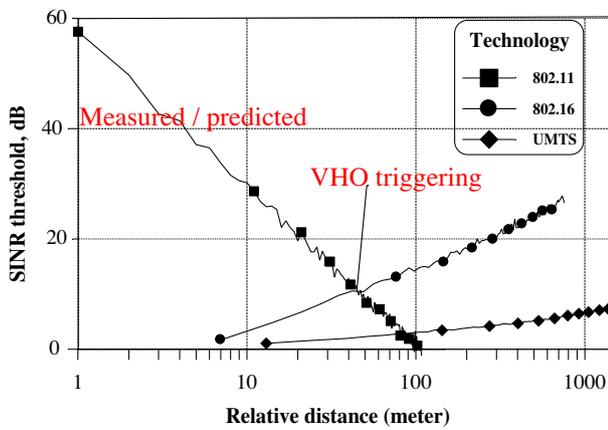


Figure 8 SINR monitoring: threshold at handoff time.

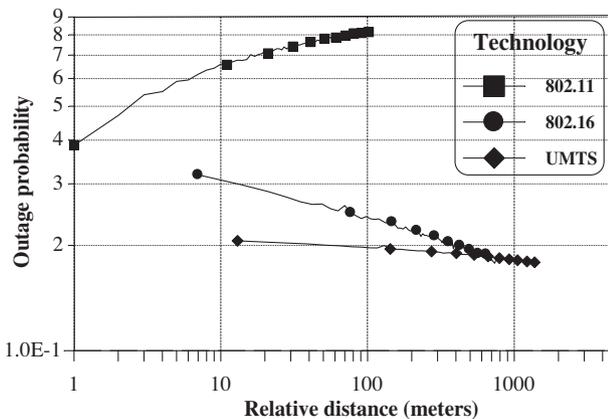


Figure 9 Outage probability monitoring at handoff time.

networks and decides as to which network it should hands off. As can be seen, the residual capacity prediction follows well the simulation results and it overcomes the significant fluctuations which is an inherited theme of the real life measurements. In the following section we present our handoff strategy.

## 6. The multi metric vertical handover strategy

This section proposes a mobility management strategy for integrated heterogeneous wireless networks. The objective is to guarantee QoS for a variety of applications with different QoS requirements. In general, the strategy can perform a complex decision criterion that combines a large number of (QoS) parameters including (in our case), outage probabilities, residual capacities, SINR thresholds in addition to network access

costs if necessary. Selection of potential network(s) will be based on a network scoring scheme that will be presented later. But, for now, the handoff process is seen to be composed of three phases: network discovery, handoff-triggering/initiation decision and handoff execution. In the following, the network discovery and handoff initiation phases are presented.

### 6.1. Handoff initiation/triggering decision

The simplest way for a multiple interface MT to discover reachable wireless networks is to keep all air-interfaces ON at all times. However, keeping an air interface active all the time consumes a great deal of battery power and bandwidth even when the MT is not sending or receiving any packets. The handoff decision refers to the process of deciding on the right moment when to trigger, perform the handoff. It is, thus, critical to avoid keeping idle air interfaces perpetually ON. Moreover, in order to avoid the ping-pong effect, MTs must observe if the neighboring network(s) is consistently better than the current one before initiating handoff.

Primarily, the SINR is monitored and used in future evolution prediction for the attached AP and neighboring networks. An example is shown in Figs. 8 and 9. Note that in Fig. 8, the SINR monitored,  $SINR_{Moni}$  represents the difference between the observed SINR and that required to satisfy the user's application requirements (Eq. (16) below), assuming that the MT is currently covered under the 802.11, and is migrating to either 802.16 or UMTS. The same scenario applies for the outage probability depicted in Fig. 9.

$$SINR_{Moni} = (SINR_{AppI} - SINR_{thr}) \quad (16)$$

Next, the handover decision function comes into play (see Section 5.1), where it helps estimating the “cross-over” moment (see Fig. 5) in order to trigger VHO procedures by starting the network scoring scheme, hence, selection of the most promising network. The following subsection presents the network scoring scheme.

### 6.2. Network scoring scheme

In VHO, we are faced with multiple QoS-criteria (e.g.,  $SINR_{Moni}$ ,  $P_{out}$ ,  $C_{rsd}$  in our case, in addition to network access cost) during handover decision making, we can no longer easily rank the candidate networks according to our preference on a single criterion.

In such cases, different criteria have to be combined and scaled in a meaningful way. In addition, various criteria in the decision process may oppose to each other, e.g., when the desirable QoS increases, it may require an undesirable increase in the price. Thus, trade-offs are sometimes required. For instance, suppose a user has to make decision among three candidate networks: 802.11, 802.16 and UMTS respectively.

Table 1A Decision matrix D.

| Network Technology | D: Decision Matrix: Monitored/Predicted Network Parameter measurements |              |               |           |
|--------------------|--|--------------|---------------|-----------|
|                    | $P_{out}$  | $C_{rsd}$    | $SINR_{Moni}$ | Cost      |
| 802.11             | 6.527380E-01   | 8.795717E-01 | 29.196250     | 6.000000  |
| 802.16             | 2.409183E-01   | 3.886717E-01 | 14.336600     | 8.000000  |
| UMTS               | 1.958555E-01   | 1.313916E-01 | 3.338140      | 10.000000 |

**Table 1B** Scaled matrix.

| Network Technology | DS: Scaled Matrix: Monitored/Predicted Network Parameter measurements |              |               |              |
|--------------------|---|--------------|---------------|--------------|
|                    | $P_{out}$   | $C_{rsd}$    | $SINR_{Moni}$ | Cost         |
| 802.11             | 3.000523E-01  | 1.000000     | 1.000000      | 1.000000     |
| 802.16             | 8.129541E-01  | 3.886717E-01 | 14.336600     | 7.500000E-01 |
| UMTS               | 1.493813E-01  | 1.313916E-01 | 3.338140      | 6.000000E-01 |

**Table 1C** Assigned weights.

| Service | P: Normalized User/Application Preferences |              |               |              |
|---------|--|--------------|---------------|--------------|
|         | $P_{out}$                                  | $C_{rsd}$    | $SINR_{Moni}$ | Cost         |
| Voice   | 4.092000E-01                               | 2.270000E-01 | 3.182000E-01  | 4.550000E-02 |
| Data    | 4.550000E-02                               | 2.270000E-01 | 3.182000E-01  | 4.092000E-01 |

**Table 1D** Network scores.

| Network Technology | Network scores    |                  |
|--------------------|-------------------|------------------|
|                    | Voice application | Data application |
| 802.11             | 7.134814E-01      | 9.680524E-01     |
| 802.16             | 6.233439E-01      | 6.004476E-01     |
| UMTS               | 5.067908E-01      | 3.613108E-01     |

The decision problem can be expressed in the decision matrix D (Table 1A), where the predicted measurements of each candidate networks are presented. Moreover, suppose that the user has two running applications, voice and data for example.

The preference on handover criteria is modeled as weights assigned by the user, as shown (for example) in Table 1C. Now, all elements in the decision matrix, D, must be in a comparable scale (Table 1B): if a QoS criterion is benefit, i.e. the larger, the better, the comparable scale is obtained using Eqs. (17) and (18), and is applicable for cost criteria.

$$y_{ij} = x_{ij}/x_i^{\max} \quad \forall i, j, \quad \text{for beneficial criteria} \quad (17)$$

$$y_{ij} = x_i^{\min}/x_{ij}; \quad \forall i, j, \quad \text{for cost criteria} \quad (18)$$

Now, the weighted average values of network scores with respect to voice and data applications are as follows: network Score = DS\*P (Table 1D).

As can be seen, with such a scoring example, Wi Fi is having the highest score for both voice and data applications,

**Table 2A** Decision matrix D.

| Network Technology | D: Decision Matrix: Monitored/Predicted Network Parameters |           |               |           |
|--------------------|--|-----------|---------------|-----------|
|                    | $P_{out}$  | $C_{rsd}$ | $SINR_{Moni}$ | Cost      |
| 802.11             | 7.807536E-01   | 2.827938  | 8.335805      | 6.000000  |
| 802.16             | 2.004737E-01   | 3.801629  | 22.529620     | 8.000000  |
| UMTS               | 1.860872E-01   | 7.452947  | 5.603825      | 10.000000 |

**Table 2B** Scaled matrix.

| Network Technology | D: Scaled Matrix: Monitored/Predicted Network Parameters |              |               |              |
|--------------------|--|--------------|---------------|--------------|
|                    | $P_{out}$  | $C_{rsd}$    | $SINR_{Moni}$ | Cost         |
| 802.11             | 2.383430E-01   | 3.794389E-01 | 3.69993E-01   | 1.000000     |
| 802.16             | 9.282390E-01   | 5.100840E-01 | 1.000000      | 7.500000E-01 |
| UMTS               | 1.000000   | 1.000000     | 2.487314E-01  | 6.000000E-01 |

**Table 2C** Assigned weights.

| Service | P: Normalized User/Application Preferences |              |               |              |
|---------|--|--------------|---------------|--------------|
|         | $P_{out}$                                  | $C_{rsd}$    | $SINR_{Moni}$ | Cost         |
| Voice   | 4.092000E-01                               | 2.270000E-01 | 3.182000E-01  | 4.550000E-02 |
| Data    | 4.550000E-02                               | 2.270000E-01 | 3.182000E-01  | 4.092000E-01 |

**Table 2D** Network scores.

| Network Technology | Network Scores    |                  |
|--------------------|-------------------|------------------|
|                    | Voice application | Data application |
| 802.11             | 3.468944E-01      | 6.239091E-01     |
| 802.16             | 8.479494E-01      | 7.831240E-01     |
| UMTS               | 7.426463E-01      | 5.791664E-01     |

7.134814E-01 and 9.680524E-01 respectively. The next example, Table 2, repeats but for measurements taken at a distance of about 80 m from the AP,

As can be seen, in this example, the current network scoring scheme has decided to migrate to the Wi MAX network, 8.479494E-01 and b7.831240E-01, but, certainly, at due time as explained in Fig. 5.

## 7. Summary and conclusions

The convergence of various wireless access technologies has always been a difficult assignment because of the fact that they have emerged independently. Future vision of wireless world is an integrated network of different wireless access technologies with improved system resources utilization anywhere, anytime. In this paper, vertical handoff procedure in location and speed-aware (via estimation) heterogeneous wireless access network is being proposed. A multi-criteria vertical handoff algorithm sensitive to various mobility and QoS parameters is analytically formulated and examined via simulations. It is targeted to estimate/predict the handoff metrics including outage probability, residual capacity, signal to interference and noise ratio threshold as well as network access cost. In order to avoid the ping-pong effect, a signal evolution prediction system is formulated and its performance is examined. The handoff scheme is triggered using an on line handoff-initiation-time estimation model. The handoff procedures begin with network scoring process based on multi-attributes strategy which results in selection of the most potential network. Simulation results are shown to track well the analytical formulations.

## Appendix A

Consider a time sequence  $X^0$  that denotes the raw of positive data measurements, (Kayacan et al., 2010),

$$X^0(X^0(1), X^0(2), \dots, X^0(n)), \quad n \geq 4 \quad (\text{A.1})$$

the following, accumulating sequence,  $X^{(1)}$ , is obtained,

$$X^{(1)} = (X^{(1)}(1), X^{(1)}(2), \dots, X^{(1)}(n)), \quad n \geq 4 \quad (\text{A.2})$$

where,

$$X^{(1)}(k) = \sum_{i=1}^k X^0(i), \quad k = 1, 2, 3 \dots n \quad (\text{A.3})$$

and, the mean sequence,  $Z^1$  is generated,

$$Z^1 = (Z^1(1), Z^1(2), Z^1(3), \dots, Z^1(n)) \quad (\text{A.4})$$

where  $Z^1(K)$  is the mean sequence such that,

$$Z^1(n) = 0.5(X^{(1)}(k) + X^{(1)}(k-1)) \quad k = 1, 2, 3 \dots n \quad (\text{A.5})$$

Then, the least square estimate sequence of the grey difference equation,  $G(t)$ , is defined,

$$G(t) = \frac{dX^1(t)}{dt} + aX^1(t) = b \quad (\text{A.6})$$

where, in the above,  $[a, b]^T$  is a sequence of parameters that can be found as follows:

$$[a \quad b]^T = (B^T B)^{-1} B^T Y,$$

where  $Y[X^0(1), X^0(2), \dots, X^0(n)]^T$  and,

$$B = \begin{bmatrix} -Z^1(2) & 1 \\ -Z^1(3) & 1 \\ \vdots & \vdots \\ -Z^1(n) & 1 \end{bmatrix}$$

The solution to Eq. (A.6) at time  $K$  is, therefore, given by,

$$X_p^0(k+1) = \left( X^0(1) - \frac{b}{a} \right) e^{-ak} (1 - e^a) \quad (\text{A.7})$$

and the predicted value of data at a future time  $(k+H)$  is,

$$X_p^0(k+H) = \left( X^0(1) - \frac{b}{a} \right) e^{a(k+H-1)} (1 - e^a) \quad (\text{A.8})$$

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