IEEE 802.21 Assisted Seamless and Energy Efficient Handovers in Mixed Networks

Huaiyu Liu[1], Christian Maciocco[1], Vijay Kesavan[1], and Andy L.Y. Low[2]

[1] Communication Technology Lab, Corporate Technology Group,
Intel, Hillsboro, OR 97124
`{huaiyu.liu, christian.maciocco, vijay.s.kesavan}@intel.com`
[2] BT Innovate, Malaysia Research Center, Kuala Lumpur, Malaysia
`andy.low@bt.com`

Abstract. Network selection is the decision process for a mobile terminal to handoff between homogeneous or heterogeneous networks. With multiple available networks, the selection process must evaluate factors like network services/conditions, monetary cost, system conditions, user preferences etc. In this paper, we investigate network selection using a cost function and information provided by IEEE 802.21. The cost function provides flexibility to balance different factors in decision making and our research is focused on improving both seamlessness and energy efficiency of handovers. Our solution is evaluated using real WiFi, WiMax, and 3G signal strength traces. The results show that appropriate networks were selected based on selection policies, handovers were triggered at optimal times to increase overall network connectivity as compared to traditional triggering schemes, while at the same time the energy consumption of multi-radio devices for both on-going operations as well as during handovers is optimized.

Keywords: IEEE 802.21, Mixed Networks, Heterogeneous Handovers, Energy Efficient Handovers.

1 Introduction

Wireless connectivity is becoming pervasive in our life. IEEE 802.11 a/b/g, IEEE 802.16, 3G and other radios are reaching price points, sizes and power consumption levels that allow for their inclusion in almost every mobile device. Due to their widely varied characteristics, no single wireless access technology can simultaneously provide a low-latency, high-bandwidth and wire-area data service to a large number of mobile users. One solution is to use a combination of multiple access technologies to provide the best possible connectivity. A future mobile terminal will be equipped with several network access interfaces, and switches between these interfaces depending on its physical environment and requirements. We refer to this multi-radio usage as Mixed Networking (MxN), where vertical handoff [1][2] (roaming across heterogeneous access technologies) is one of the most important features.

Traditionally, network selection has been based on evaluation of the received signal strength (RSS): e.g. an access point with the strongest RSS is selected. In MxN, such physical characteristics are usually not directly comparable. Besides, we need to

C. Giannelli (Ed.): Mobilware, LNICST 0007, pp. 27–42, 2009.

consider additional factors such as monetary cost, power consumption, network conditions, terminal conditions, and user preferences. In [1], multi-radio architectural issues were explored, and a neural-network-based network selection algorithm was developed to satisfy user bandwidth requirements. In [3], a policy-enabled handoff decision algorithm is proposed along with a cost function that considers several of the factors mentioned above. Further, several optimizations to the handoff decision process are proposed in [4][5]. While significant work has been done on network selection initiated on the mobile device side, there is no literature available describing how mobile devices and network operators can cooperate to achieve an optimal network selection in a deployable approach. This is an area where the 802.21 standard [6] will facilitate the exchange of information between these entities to enable the mobile device to obtain relevant network information, including link layer triggers or higher layer information elements.

In this paper, a cost-function-based network selection architecture assisted by the 802.21 standard is investigated. Such an algorithm is flexible and can take into account the relevant factors with minimal user involvement. 802.21 is defining a generic media-independent-handoff (MIH) framework to support information exchange between network elements that support network selection, as well as a set of functional components to execute the roaming process. The 802.21 event service provides early indication of upcoming lost connectivity, therefore enabling pro-active action for network selection and a smoother handoff. The 802.21 information service provides data that enable a mobile client to optimize networks scanning frequency and enable energy efficient network selection. To the best of our knowledge, there has been no work on using 802.21 to optimize network selection in an energy efficient manner using real environment data. We show in this paper that using additional information provided by 802.21, we can achieve significant energy efficiency improvement for mobile devices without significant overhead. Using prediction of loss of network connectivity we show that session continuity is also improved.

The rest of the paper is organized as follow. In Section 2, the background of this research, our handoff system architecture and its elemental technologies are explained. In Section 3, our network selection architecture assisted by IEEE 802.21 is discussed in detail, and evaluated in Section 4, using a multi-radio system and usage scenario (Wi-Fi, WiMAX, and HSDPA). Finally, we conclude in Section 5.

2 Background and Related Work

2.1 IEEE 802.21 Media Independent Handover

There are currently various efforts underway in standard organizations and industry forums to standardize heterogeneous handovers, including IEEE 802.21 [7] and 3GPP SA WG2 [14]. For instance, IEEE 802.21 specifies three media-independent services: event service, command service, and information service.

Media-Independent Event Service (MIES) indicates changes in state and transmission behavior of the physical, data link and logical link layers, or predict state changes of these layers. Events defined include Link-Parameters-Change, Link-Up (LU), Link-Down (LD), Link-Going-Down (LGD), etc. LGD may be used by upper layer entities, such as Multi-radio Connection Manager, to search for a new point of attachment before the current one ceases to carry frames, thus reduce the handover delays between attachment points.

Media-Independent Command Service (MICS) defines a set of primitives or handover commands that allow clients and/or networks to initiate and coordinate the handover process from one network to another.

Media-Independent Information Service (MIIS) provides a data store of available networks and network parameters, and defines standard query/response messages to access and retrieve such information for each available access network. Such information is critical for the handover process. For instance, the information of available networks is very useful for optimizing the network selection process.

2.2 Mixed Network Architecture

On the client side, the vertical handover process can be classified into three steps, i) "when and why" should the device transition to a new network, ii) "where" should the device transition to, and iii) "how" should the device transition between networks? The "when and why" step corresponds to what we describe as the triggering process when the mobile device receives an indication that it should operate on another network. This indication can be generated by external condition such as signal degradation, by device level condition such as critical battery level requiring a switch to a more energy efficient network, or be user initiated. The "where" step is when the mobile device selects on which network to operate, either on a similar network type (a homogeneous network) where a link layer transition is sufficient, or on a heterogeneous network where both network and service transitions need to be performed. The last step, the "how" is defining the execution of the handover and how the device performs the transition, e.g. either doing a horizontal handover to transition to a similar network or a vertical handover using techniques like break-before-make or make-before-break.

Intel and BT have collaborated to prototype a WiFi/WiMax multi-radio system in the BT 21CN environment [7]. Figure 1 shows the high level architecture of the prototype at the client side, which we refer to as the MxN architecture. Applications can use the services provided by the MxN system through the MxN interface. These services include 802.21 MIH services, connection management and network adaptor management. Applications such as VPN and SIP-based applications that are not capable of switching across adaptors can use the connection management service. Connection managers from other parties can use the MIH and adaptor management services alone and handle connection management themselves. The MxN architecture also defines an adapter control layer that spans across various adapters and provides the ability to interface with the adapters. To handle session mobility we used SIP for the session initiation and control protocol.

For the function blocks inside the MxN system, the Smart Triggers block addresses the "when and why" step in a handover, and provides the mechanism to monitor changes to MAC and PHY state, including link triggers. The Information Exchange block interfaces with Information Server (in the networks), retrieve network information, and provide it to the Network Selection engine, which then chooses the best network to operate on. Together these two address the "where" step. Finally, the Network Switching module work closely with SIP to address the "how" step.

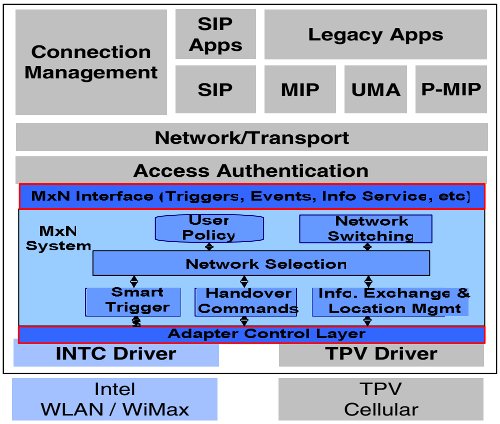


Fig. 1. MxN Architecture

The work in this paper focuses on the Network Selection module and the Information Exchange & Location Management module.

2.3 Smart Handover Trigger

We have developed a smart trigger scheme [8]. The purpose of the smart trigger scheme is to provide ***accurate*** and ***predictive*** link layer triggers to enable seamless handovers and minimize service interruption. It addresses how to detect link status changes (e.g. Link-Going-Down) and how to accurately predict such changes. The ability to predict link triggers accurately and early in time, especially the Link-Going-Down and Link-Down triggers, will send early warnings to entities such as connection managers and give it extra time to prepare for handover and seamlessly transfer application sessions, hence further reduce the service interruption.

In the smart trigger scheme, we used signal strength to reflect link quality, such as RSSI for WiFi networks and CINR for WiMax networks. For trigger generation, we first apply an exponential moving-average filter to smooth out raw RSSI measurements that fluctuate, then compare the smoothed RSSI to predefined thresholds and generate link triggers when necessary. The smart trigger scheme also includes a trigger prediction step. A link trigger is predicted based on predicted future (smoothed) RSSI values using a long as well as short history window. Then trend analysis algorithm is used to analyze the long and short term trends of RSSI. Evaluation and implementation of the algorithm based on real WiFi and WiMax devices demonstrate that our algorithms provide early and accurately prediction. In Section 4, we will also analyze the performance benefits for network selection by using different triggering schemes.

2.4 Cost-Function-Based Media Independent Handover

A policy–based network selection algorithm with a cost function is first introduced in [3] and several optimizations to the algorithm and cost functions are proposed in [4][5]. As described in [4], in MxN, the network with the lowest cost is the network that would provide the most benefit to the user and is the optimal handoff target, *n_opt,* which is determined as follows:

$$n\_opt = \min(C^1, C^2, ..., C^n)$$

where C^n is the cost function evaluated for network *n*. C^n includes the cost of receiving each of the user's requested services from network *n*, and it is calculated:

$$C^n = \sum C^n_s, \text{ where } C^n_s = E^n_s Q^n_s.$$

Here *s* is the index representing the user-requested services, C^n_s is the per-service cost function for network *n*, E^n_s is the network elimination factor for requested service *s* at network *n*, and Q^n_s is the QoS factor for service *s* at network *n*. E^n_s is used to filters out networks that cannot guarantee the QoS constraints expected by a service. Q^n_s is calculated as follows:

$$Q^n_s = \sum_j W^n_{s,j} Q^n_{s,j},$$

where $Q^n_{s,j}$ is the normalized QoS provided by network *n* for parameter *j* for service *s*, and $W^n_{s,j}$ is the weight indicating the impact of the QoS parameter on the user or the network.

According to [3], the natural log is used as the normalization factor. If a network offers twice as much bandwidth, but is twice as expensive as the other network, then they are considered these as equally good (this means they have the same cost). The property of logarithm $\log a - \log b = \log(a/b)$ can reflect this logic.

For example, a cost to use network *A*, C^A, is calculated as below. This is when only bandwidth, delay, and power consumption are in consideration, and network *A* is abstracted as 1Mbps, 10ms, 900mW. Additionally, weights on bandwidth, delay, and power are assigned 0.5, 0.1, 0.4, respectively.

$$C^A = 0.5\ln(\frac{1}{1000}) + 0.1\ln(10) + 0.4\ln(900) = -0.502661$$

In the past, cost functions only consider traditional network properties like bandwidth, delay and power. With 802.21, we now have the ability to also consider the physical location of networks, the services offered by these networks, security requirements, etc, which can be used to optimize the network selection process.

3 IEEE 802.21 Assisted Network Selection

The cost function and the elimination function together enable network selection and are integrated in the MxN architecture (Section 2.2) as shown in Figure 2. The inputsto the network selection block can be broadly classified as (i) a comprehensive list of networks (ii) network commands and (iii) network and device conditions. The network selection logic considers these inputs in the context of user preferences and

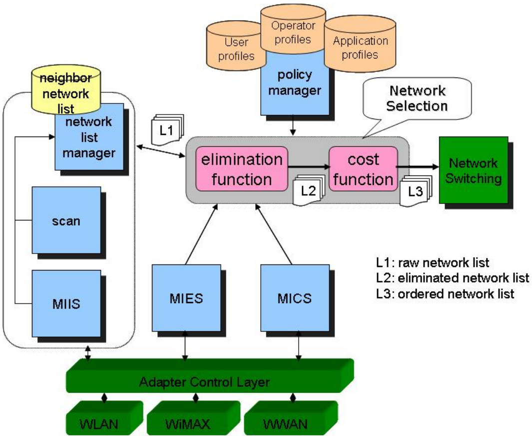


Fig. 2. MxN Network Selection Architecture

policies, resulting in an ordered list of networks for connectivity. In this paper we explore how the primitives defined in 802.21 can be used with the cost-based function to select a network in an energy efficient way.

The criteria that govern the selection of one network over another in MxN are policies. The policies include several parameters like monetary cost, bandwidth, latency, power etc to which weights can be associated to indicate importance of one parameter over another. The policies can be configured by the user, e.g. always connect to the network that offers highest bandwidth; set by the network operator, e.g. when home network is unavailable only connect to the operators who have roaming agreements; or requested by applications running on the mobile device. The first step in network selection is the discovery of networks. A rudimentary way of network discovery is periodic scanning on all the radios in the device. However, scanning is a power intensive process. Usually network discovery is optimized by building a local repository of previously visited and scanned networks. Most modern mobile device support GPS capability, which can be used to store network coordinates. While this optimization reduces periodic scans in previously visited locations, scanning cannot be avoided in new locations. 802.21 MIIS provides a repository of networks and their static parameters. Using a standardized query/response mechanism, devices can retrieve information about different networks using any network interface to build a network map. The ability of discovering new networks, independent of the connected media, minimizes scanning operation on network interfaces and the time for these interfaces to remain in the ON state, therefore extending the battery life. Figure 3 compares state machines of the scanning operations, with and without MIIS service. If the network map from MIIS indicates there are no networks in the vicinity the radio need not be turned ON for scanning. If the network map indicates the presence of a network, the elimination function checks to see if the network's parameters, as provided by MIIS service, satisfies all the policies and only then is the network considered as a potential candidate in network selection. Thus the information from MIIS along with the elimination function is able to further reduce scanning operations and improve the battery life of the device.

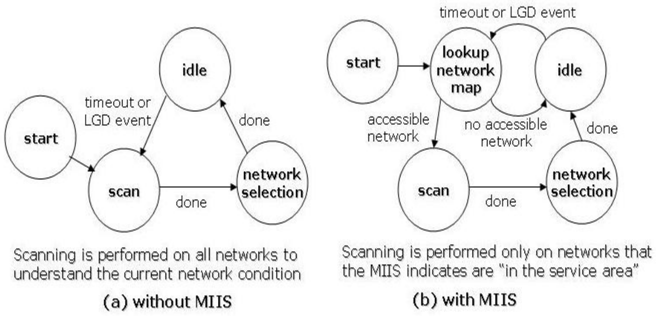


Fig. 3. Scanning and Radio-On-Time Optimization

The network selection process is triggered by any of the following events: (i) the physical location of the mobile device changes and new networks discovered using MIIS, (ii) current network conditions change as indicated by MIES, (iii) device receives handover command from the network, and (iv) policy changes initiated by user, application or operator. The focus of our research is to obtain network maps from MIIS service and detect link-going-down by implementing MIES functions, and provide this information to the elimination-based cost function to enable energy efficient handover.

4 Evaluation

4.1 Network Selection Simulator

In order to evaluate different network selection algorithms, we have implemented a network selection simulator. The architecture of the simulator is shown in Figure 4.

The simulator consists of three main components: Network Selector (with cost function), Access Network, and Mobile Node. Network selector implements the network selection algorithm, where information used in the algorithm is obtained from the other components. It also implements the cost function to calculate the cost

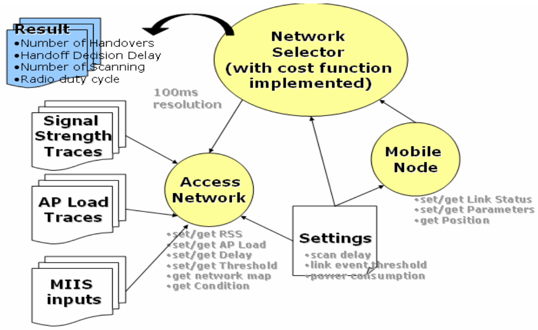


Fig. 4. Simulator architecture

Table 1. Implemented features in the simulator

Feature	Description
Trigger	Moving average (50 RSSIs window)
	Smart Trigger (Exponential average) Smart Trigger (Exponential average with prediction)
Network Selection	Static Preference (WiFi>WiMax>3G)
	Cost Function

of each access network regarding the current conditions of the Mobile Node. Mobile Node provides conditions such as the name of the current network, status (during communication, scanning, or handoff), and static information (number of handoff, number of scanning, etc.). Access Network provides conditions of available networks, where signal strength and AP load histories were considered in the simulations. Finally, MIIS inputs provides network information that could be obtained from MIIS service. For each simulation, we recorded the number of handoffs, number of scans, and radio duty cycle. We have implemented three trigger methods and two network selection algorithms as listed in Table 1.

The simulations were based on a scenario that a user living in a suburban area goes to his office in a city area, as shown in Figure 5(a), where each circle represents the approximate coverage area of each network along the route. RSSI/CINR traces as the user travels from home to office are shown in Figure 5(b), where x axis is the time, and y axis is the RSSI/CINR value the users device would see in the corresponding time. Network 1 is a Wi-Fi network at home. Network 2 is an HSDPA based 3G networks which covers the entire route. Network 3 and Network 4 are WiMax networks that cover the city area. Network 5, 6, 7, and 8 are office Wi-Fi networks. The assumption is that the trip from home to office takes 30 minutes.

The RSSI and CINR traces shown in Figure 5(b) were collected from real networks. The RSSI traces for Networks 5 to 8 were collected by walking inside Intel office buildings with a laptop equipped with Intel 3965 wireless card. The RSSI trace for Network 1 was collected by walking from inside to outside of a house, using the same laptop. The CINR traces for WiMax networks were collected driving in field trials where WiMax base stations were deployed (Hillsboro, OR). Similarly, the 3G (HSPDA) RSSI trace was obtained by driving along a route in Hillsboro, OR, using a

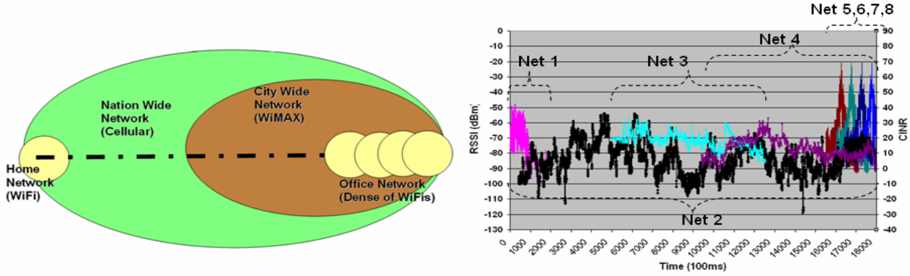


Fig. 5. (a) Network coverage, and (b) the RSSI/CINR trace of each network used in simulations

laptop with a Sierra Wireless card connecting to AT&T network. We assume the mobile device is a phone type of device and it always maintains its connection to cellular networks for phone calls. However, for data transmission, it needs to choose the most appropriate networks, where the network selection is applied.

In our simulation, AP (or BS) load is defined as total traffic currently served by an AP. The traces of AP loads are generated for each network based on a Markov Modulated Poisson Process [9]. In practice, AP load can be estimated or obtained in several ways. For example, AP load in WiFi network could be obtained if APs support 802.11k, or by using methods as proposed in [10]. Estimation of cellular or WiMax networks might be done considering the modulation and coding scheme a BS supports, as well as the received signal level on the broadcast channel, the carrier-to-interference power ratio ("C/I"), and the raw BER estimate [11].

The cost function used in the experiments is as follows:

$$C = W_B \ln\frac{1}{B} + W_P \ln P + W_C \ln C$$

where B denotes available bandwidth, P the power, and C the monetary cost.

In our simulations, to get the available bandwidth of an AP or BS, we subtracted the AP's load from the highest data rate that can be provided by the network (this information could be provided by MIIS service). For WiFi networks, we assume they are 802.11b APs with 11 Mbps data rate; for WiMax, we assume 30 Mbps data rate (the data rate depends on the modulation scheme, the coding scheme, etc [12]); and for 3G, we assume 1.2 Mbps data rate. Effectively estimating available bandwidth is an active research area and beyond the scope of this paper.

For monetary cost, we assume that WiFi is of flat cost (a fixed monthly fee), while costs for WiMax and 3G access are based on the amount of bytes transmitted through that network; and we assume that WiMax costs somewhat less than 3G. (In practice, the monetary costs could be different, for instance, WiFi may cost a lot higher when the user is in a hotel.) For power consumption, studies have shown that 3G card consumes more transmit power than WiFi card [13], partly due to the long radio range. For the same reason, we assume that WiMax redio consumes higher power than WiFi in transmission (but less than 3G).

4.2 Performance Analysis

Our ultimate goals for network selection and seamless handover are to select the most appropriate network, optimize for energy efficiency, and switch at the best timing. In this section, we evaluate our algorithms in each aspect of the goals.

4.2.1 Network Selection

To study the effectiveness and flexibility of cost-function-based network selection, we run experiments with different weights for each factor in the cost function. Figure 6 and Figure 7 show some snapshots of network selection in areas that were under coverage of all three networks.

Figure 6 shows some results where the weight of one of the parameters in the cost function was assigned 1. The number on each bar is the cost as calculated using the

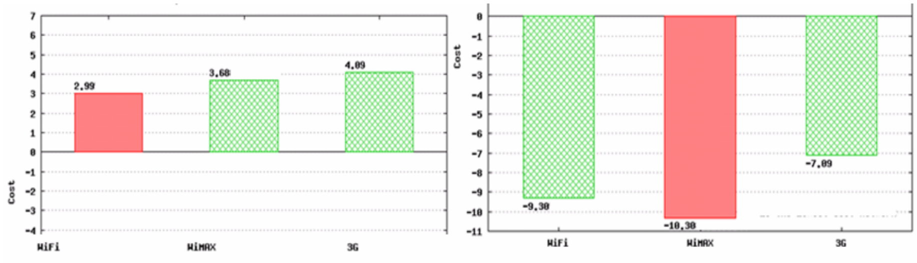


Fig. 6. Network selection, (a) $W_C = 1$, (b) $W_B=1$

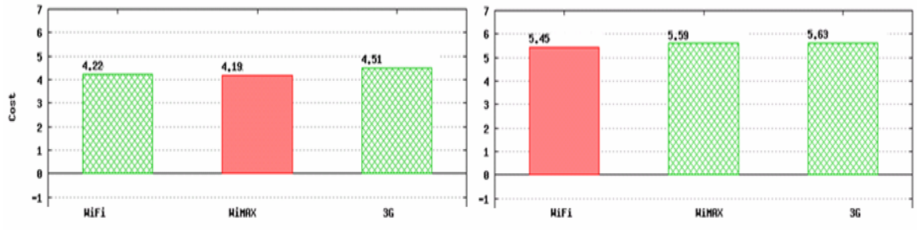


Fig. 7. Network selection, (a) $W_B = 0.1$, $W_P = 0.9$ (b) $W_C=0.1$, $W_P=0.9$

cost function. The solid bar represents the network selected after applying the cost function. In Figure 6(a), the weight of monetary cost is assigned 1 and the WiFi network was selected. In Figure 6(b), the weight of bandwidth is assigned 1, and the WiMax network was selected. The results in this figure demonstrate that with certain weight assignments, cost function enables similar selection as using a static network selection method.

Figure 7 shows some results where different weights were assigned to different factors. In both experiments, the weight of power is assigned 0.9. In the experiment in Figure 7(a), the weight of bandwidth was 0.1, while in Figure 7(b), the weight of monetary cost was 0.1. Hence, in both experiments, power is the utmost factor in selecting an access network, yet the selection in Figure 7(a) should result in higher potential available bandwidth and the selection in Figure 7(b) should result in lower monetary cost. As we can see from Figure 7, WiMax was selected in the first experiment, while WiFi was selected in the second experiment (recall that both are more power efficient than 3G). The results demonstrate the flexibility of cost function to take different factors into consideration.

Figure 8 shows the results of network selection along time in two simulations that have different weight settings. The top one has the settings of “max battery life” (more weight was given to the power factor), while the bottom one has “max throughput” (more weight was given to the bandwidth factor). Due to the limited coverage of WiFi/WiMax networks as in Figure 5(a), choices of network selection were limited to one or two networks in some time of each simulation. For instance, in the first 2 minutes, only Network 1 (WiFi) and Network 2 (3G) were available, in the next 6-7 minutes, only Network 2 was available. Hence, the selected networks in the two diagrams in Figure 8 look similar in many time points. However, the times that

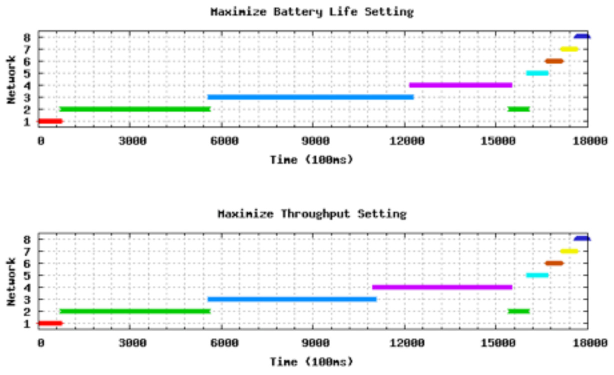


Fig. 8. History of active network for different settings of cost function

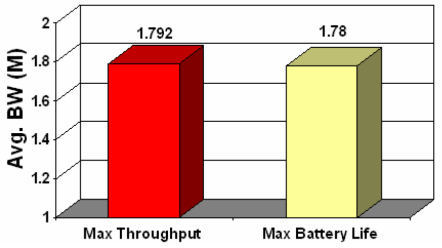


Fig. 9. Average bandwidth comparison for different settings of cost function

Networks 3 and 4 were selected were different. In the "max throughput", Network 4 was selected earlier than in the "max battery life", due to higher estimation of AP available bandwidth of Network 4 than that of Network 3.

To demonstrate that the selections in the "maximize throughput setting" resulted in higher available bandwidth, we plotted the average available bandwidth in both settings, as shown in Figure 9. (Recall that the available bandwidth was calculated as the amount of highest possible data rate minus AP load). As we can see from the figure, by making different selections between Network 3 and Network 4, the average available bandwidth (averaged across the entire 30 minutes of simulation) in the "max throughput setting" is higher that the other setting.

4.2.2 Energy Efficient Network Selection with MIIS

Applying MIIS support can reduce both handoff delay (by reducing the time for network discoveries) and power consumption during network selection. In this section, we focus on studying the power saving benefit by applying MIIS.

As explained before, the operation in the network selection process that consumes the most power is scanning for available networks and obtaining necessary information. Typically, without MIIS optimization, to discover and obtain network information in time, WiFi networks are scanned once a minute (e.g. every minute Windows ZeroConfig queries driver for network update), and cellular networks are

Table 2. Average platform power increase due to periodic scan, based on measurements on Ultra Mobile PC

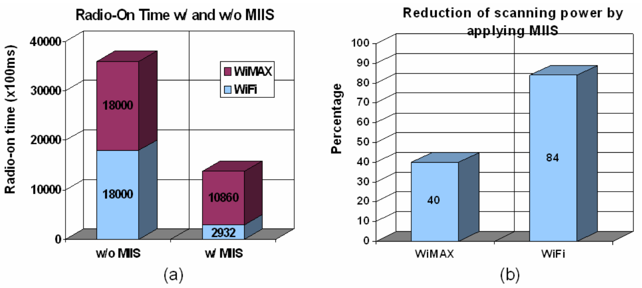
Radio type	Mobile device's power consumption increase when radio periodically scans for networks before connection is established (averaged across time)
WiFi	100mw
Cellular	200mw-600mw
WiMax	100mw-300mw

scanned every 30 seconds to 1 minutes until a connection is established. With MIIS, however, a mobile device only needs to scan a network if it is in its coverage area and has access to such a network. For example, the device needs to scan for WiFi networks only when it is in WiFi coverage and has access to at least one of the WiFi networks in range. (To identify network coverage, the device needs to know its location. The location could be obtained by the cell tower technology provided by cellular networks. It could also be obtained by using a GPS radio, however, continuously using GPS radio consumes significant power). Our measurements indicated that if the WiFi radio goes to low power mode after each scanning, then when WiFi radio scans every minute, on average a mobile device's (e.g. an Ultra Mobile PC) power consumption increased by about 100mw over time. When cellular radio scans every minute, the device's power consumption increased 200 to 600mw (power consumption varies with different radio chipsets). For WiMax, our measurements indicate 100 to 300mw increase of platform power. Hence, significant amount of power would be saved by disabling scanning or even turning off radio, if it is known that a radio is out of the coverage of accessible networks.

To evaluate the energy savings enabled by applying MIIS service, we assume that for each radio, the scanning power is the same when it is connected to a network or not.[1] Also, since we assume that 3G is always available in the simulation setup, and the mobile device maintains the 3G network connection all the time, we only compare the scanning power consumptions for WiFi and WiMax radio below. As shown in Figure 10(a), without MIIS service, the radio has to remain on and scan for networks all the time (although it may go to low power state after each scan), in order to obtain information for network selection. With MIIS service, when a radio is out of coverage, there is no need to turn it on for scanning during that period. Hence the radio-on time is greatly reduced especially when networks are far less than 100% of coverage. Figure 10(b) shows that by turning off a radio, the proportion of scanning power has been saved. For WiMax, since 40% of time the mobile device was out of coverage, at least 40% percent of scanning power could be saved; and for WiFi, 86% of scanning power could be saved.

---

[1] This might not always be the case in real implementations. Once a device is connected, scanning process to update network information can be provided by current network, and hence could cost less power than when the radio is not connected. Note that in this case, majority of scanning power is consumed when a radio is not connected, hence the proportion of scanning power saved by applying MIIS would be even higher than the results in Figure 10(b).



(a) (b)

Fig. 10. Power saving benefit by applying MIIS

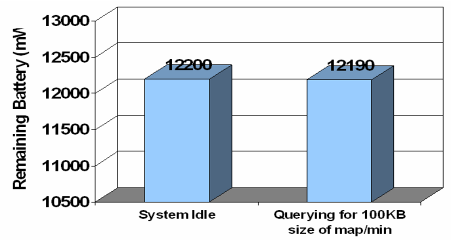


Fig. 11. Energy overhead of MIIS querying for 1 hour

Therefore, MIIS optimization is especially useful when there is a significant portion of time that a device is out of coverage of some networks. Network coverage varies a lot depending on where people live, their daily commute pattern, etc. By collecting traces from different people's daily life, a recent study [13] shows that on average, 49% of time a person is within WiFi coverage. In the future, it is still unlikely that WiFi coverage will be 100%. WiMax and 3G have better coverage, however, right now they are much less than 100% of coverage and will likely to remain under 100% at least in the near future. Hence, by applying MIIS optimization, significant amount of power could be saved by avoiding unnecessary scanning.

On the other hand, there is some overhead associated with MIIS optimization. Querying for and retrieving MIIS information also consumes power. In order to evaluate this energy overhead, we did some empirical experiments in which a Sony UMPC (VAIO UX280P), with Windows XP installed, is connected with a WiFi AP and a laptop serving as the MIIS server was also connected to the AP. We did two sets of experiments. In one set, the UMPC simply stayed connected to the AP and remained idle. In the other set of experiment, the UMPC queried 100KB of MIIS response every 5 minute. Note that 100KB of MIIS response carries more than 2000 Wi-Fi APs information. The average remaining battery capacities from each set of experiments are plotted in Figure 11. As we can see, the average power consumption by querying MIIS information every 5 min is about 10mw, much lower comparing to that of periodic scanning.[2] We also did experiments of pulling 1000KB of MIIS

---

[2] The power consumption for fetching MIIS information with 3G or WiMax radios could be slightly higher, since communication range of these radios is longer and hence transmission power is higher.

responses every 5 minutes. The average power consumption was similar. In reality, MIIS information could be pulled less often, and each time with a slightly large amount of response (say every 30 minutes of 1000KB responses instead of every 5 minutes of 100KB), and hence further reduce the corresponding power consumption.

Note that in reality, the MIIS server is more likely to be multiple hops away from a mobile device, since such server usually resides inside some network. However, more hops only increase the delay in receiving the responses, and since the mobile device's radio could go to low power mode while waiting for the response, the power consumption would not increase much due to longer delays.

4.2.3 Triggering Methods Comparison

Finally, we study the triggering time of handovers and its impacts on quality of connections. As implemented by most WiFi drivers, a handover trigger is generated if the average signal strength is below a threshold, where the average value is obtained by averaging across the past signal strength measurements. We refer to this method as the "average" method.

In our handover algorithm design, we applied our smart trigger scheme to initiate a handover process. The objective of smart trigger is to provide early and accurate indication to a Connection Manager (CM) and hence gives the CM enough time to discover surrounding networks, select the most appropriate one, and establish connection on that network before the current network's quality goes too bad (i.e. to enable make-before-break). In this section, we present some results that demonstrate the advantage of the smart trigger scheme over the traditional average method. We use the metric "link-up time" to measure the quality of connections. By link-up time, we mean the amount of time that the signal strength of the current connection is above a certain Link-Down threshold, for instance, -80dB for WiFi networks, -110dB for cellular networks, and 0 (CINR) for WiMax networks. The longer the link-up time, the better the quality of connections is.

Figure 12 highlights the connection and signal quality of the current network from simulation time 70s to 100s during one simulation. For each time point, if the current selected network was in link-up status (that is, the signal strength is above the Link-Down threshold), a point was plotted in the figure. In other words, gaps between the points indicate the signal quality during that period was below a minimum threshold to maintain connectivity. The top graph in Figure 12 shows that around time 76s, the device switched from WiFi to 3G network. On the contrary, in the bottom graph, where the traditional average method was used for handover triggering, the device did not switch from WiFi to 3G until around 91s. As we can see, in the bottom figure, from 76s to 91s, there were many gaps between the points, indicating more time of bad signal quality before handover happened.

Figure 13(a) shows the total link-up time from the same experiment. Similar trend was observed in other experiments. Among the 1800s of total simulation time, using the average method for handover triggering resulted in 1759 sec of connected time, while using the smart trigger method resulted in 1778 sec of link-up time. Clearly, the smart trigger method provides the benefit of fast and accurate prediction of link quality and enables handover to a different network before link quality becomes too bad. Note that differences between link-up times are due to the triggering time of handovers. The handover itself, although may introduce some short time interruption between connections, does not contribute to the link-up time as we defined above.

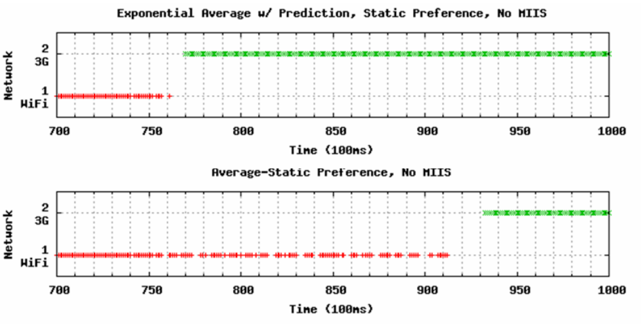


Fig. 12. Trigger Methods Comparison (70s-100s): “Smart Triggering” (Exponential Average with Prediction) vs. “Average”

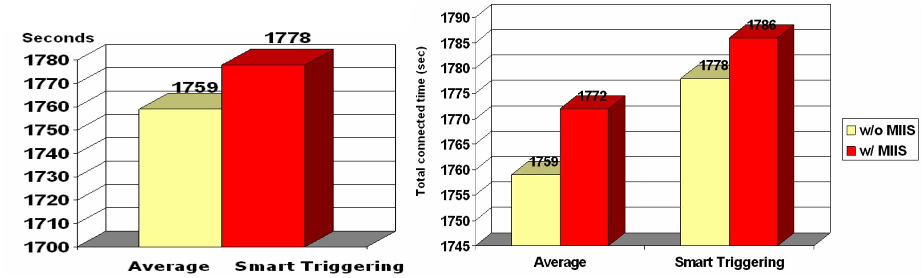


Fig. 13. (a) Total connected time (b) Total connected time comparison with or without MIIS optimizations

This is because handover only happens after it is triggered by the triggering method and the handover delays are the same in both cases (as they both switched from WiFi to 3G) no matter what trigger method is used.

Figure 13(b) shows the comparison of total connected time when using and not using MIIS service. Together with a trigger method, MIIS could help provide better connectivity. This is because unnecessary scanning has been eliminated so that service interruptions due to off-channel scanning have also been eliminated.

5 Conclusion

For multi-radio devices the overall energy consumption of the device is a key issue as the number of radios on these devices increase while at the same time end-users expect a seamless connectivity across all radios. To address these issues we have developed a flexible network selection architecture to optimize seamless operation as well as the energy efficiency of these devices. As a component of this architecture, our research on handover triggers providing early indication of connectivity improves the seamless aspect by optimizing the connected time. In this paper, starting from a known mechanism to perform network selection using a cost function, we enriched this mechanism by using additional properties of the mobile devices and access networks, provided by an 802.21 Information Server, to optimize the network selection for optimal energy efficiency. Under a realistic scenario with real network traces for a multi-radio device, our optimized network selection algorithm showed a power saving opportunity of up to 40% for WiMax and 80% for WiFi. The 802.21 Information Service provides information that enables the device to reduce its scanning frequency and optimize the network selection with limited energy overhead. We also showed that there is almost negligible energy cost to acquire the required additional information from the 802.21 Information Server using an appropriate request rate. As a next step, we are integrating this optimized network selection algorithm into our existing multi-radio WiFi/WiMax multi-radio prototype.

Acknowledgment. The authors thank Koshiro Mitsuya for his contributions during his time in Intel Corporation.

References

[1] Pahlavan, K., Krishnamurthy, P., Hatami, A., Ylianttila, M., Makela, J.P., Pichna, R., Vallstron, J.: Handoff in Hybrid Mobile Data Networks. Personal Communications 7(2), 34–47 (2000)

[2] Stemm, M., Katz, R.H.: Vertical handoffs in wireless overlay networks. Mobile Networks and Applications 3(4), 335–350 (1998)

[3] Wang, H.J., Katz, R.H., Giese, J.: Policy-Enabled Handoffs Across Heterogeneous Wireless Networks. In: Proceedings of the 2nd Workshop on Mobile Computing Systems and Applications (WMCSA), New Orleans, LA (1999)

[4] Fang, Z., McNair, J.: Optimizations for Vertical Handoff Decision Algorithms. In: Proceedings of IEEE Wireless Communications and Networking Conference (WCNC), Atlanta, Georgia (2004)

[5] Fang, Z., McNair, J.: Multiservice Vertical Handoff Decision Algorithms. EURASIP Journal on Wireless Communications and Networking 2006(2), 52–64 (2006)

[6] IEEE P802.21/D14 (October 2008)

[7] Choong, K.N., Kesavan, V.S., Ng, S.L., de Carvalho, F., Low, A.L.Y., Maciocco, C.: SIP-based IEEE802.21 media independent handover — a BT Intel collaboration. BT Technology Journal 25(2) (April 2007)

[8] Liu, H., Maciocco, C., Kesasvan, V.S., Low, A.: A Smart Triggering Scheme to Reduce Service Interruption During Heterogeneous Handovers. In: IEEE International Conference on Dependable Systems and Networks (DSN) (2008)

[9] Muscariello, L., Mellia, M., Meo, M., Lo Cigno, R., Marsan, M.A.: A Simple Markovian Approach to Model Internet Traffic at Edge Routers, COST279, Technical Document, No.TD(03)032 (May 2003), `http://www.tlc-networks.polito.it/muscariello/papers/279TD-03-032.pdf`

[10] Chen, J., Cheng, T., Zhang, T., van den Berg, E.: Effective AP Selection and Load Balancing in IEEE 802.11 Wireless LANs, GlobeCom (2006)

[11] Schramm, P., Peter, F.M., Olofsson, H.G.: Cell selection in mobile radio systems, US Patent 6542742

[12] IEEE Std 802.16-2004, Table B.29

[13] Rahmati, A., Zhang, L.: Context-for-Wireless: context-sensitive energy-efficient wireless data transfer, MobiSys (2007)

[14] 3GPP Architecture Enchancements for non-3GPP accesses (3GPP TS 23.402)