2008-09-29

Autonomous and Intelligent Radio Switching for Heterogeneous Wireless Networks

Qiuyi Duan
qiuyiduan@gmail.com

Charles D. Knutson
knutson@cs.byu.edu

Lei Wang

Daniel Zappala
daniel_zappala@byu.edu

Original Publication Citation

Qiuyi Duan, Lei Wang, Charles D. Knutson and Daniel Zappalla. "Autonomous and Intelligent Radio Switching for Heterogeneous Wireless Networks." Proceedings of the Fourth IEEE International Workshop on Heterogeneous Multi-Hop Wireless and Mobile Networks 28 (IEEE MHWMN'8), Atlanta, Georgia, September 29, 28.

Autonomous and Intelligent Radio Switching for Heterogeneous Wireless Networks

Qiuyi Duan, Lei Wang, Charles D. Knutson and Daniel Zappala
Computer Science Department
Brigham Young University
Provo, UT 84602-6576
{qiuyi,lei,knutson,zappala}@cs.byu.edu

***Abstract*—As wireless devices continue to become more prevalent, heterogeneous wireless networks – in which communicating devices have at their disposal multiple types of radios – will become the norm. Communication between nodes in these networks ought to be as simple as possible; they should be able to seamlessly switch between different radios and network stacks on the fly in order to better serve the user. To make this a possibility, we consider the challenging problems of when two communicating devices should decide to switch to a different radio, and which radio they should choose. We design an *Autonomous and Intelligent Radio Switch* (AIRS) decision algorithm that uses predicted radio availability and user profiles to choose the best available radio for two adjacent devices. The decision algorithm uses several parameters to avoid switching radios too frequently. We use a simulation study to evaluate the best settings for several parameters, then show that the AIRS system performs better than several alternative algorithms. AIRS is able to provide dynamic, but stable radio switching, while balancing the competing objectives of high throughput and low power consumption.**

I. Introduction

As wireless devices continue to evolve, systems that support multiple radios are becoming increasingly common, because no single wireless technology provides the desired functionality in all situations. Cellular technology provides coverage over a wide area, but phone manufacturers are adding WiFi interfaces so that users can browse the web at a WiFi hotspot, with lower connection charges and possibly higher speeds. Likewise, laptops and cellphones, in addition to WiFi or cellular interfaces, have Bluetooth interfaces for exchanging data directly with other devices or peripherals when other network interfaces may be unavailable, too cumbersome, or consume too much power.

Likewise, wireless networks are likely to be composed of heterogeneous devices in the future. Mesh networks will need multiple radios, so they can communicate with mobile devices that may switch among different radios to conserve power or provide greater throughput. Ad hoc networks will be composed of many heterogeneous devices, and will need to find ways to adapt to radio availability when these devices move. In both cases, devices ought to be able to seamlessly switch between available radios on the fly in order to provide continuous access to available services. Communication ought to "just work", rather than requiring the user to be involved.

One of the key challenges for a heterogeneous wireless network is deciding when to switch radios and which radio to choose. In a multi-hop network, a flow may span several hops, and each pair of adjacent devices in the flow may experience different amounts of interference, mobility, and competing traffic. Hence, the radio switching decisions for a given flow can be decomposed into a series of negotiations between adjacent nodes. For each pair of nodes, several radios may be available, so the devices must choose the one that will provide the best performance. This type of radio switching is typically classified as a *soft, vertical handover*, meaning that multiple radios are available and that each radio typically has a different network stack.

In this paper, we develop an *Autonomous and Intelligent Radio Switching* decision algorithm that has several unique features. First, it takes as input the predicted link quality of each radio link, rather than using only current measurements of availability. Second, it also takes as input user preference, so that it can make decisions based on whether the user wants to optimize throughput or battery power. Third, it can choose the best available radio according to preference ranking (based on throughput or power savings) or by calculating expected utility, which provides a balance between throughput and power. Finally, the algorithm includes mechanisms to avoid the overhead of frequently switching radios when their availability is sporadic.

We evaluate the AIRS decision algorithm using a simulation study of heterogeneous wireless devices. First, we determine the appropriate settings of several parameters that help the decision algorithm to avoid frequent switches. We illustrate its effectiveness by showing how the decision algorithm avoids using radios that are only sporadically available, as well as ignoring brief periods of unavailability for a preferred radio. Finally, we show that the algorithm provides better throughput and power savings compared to alternative algorithms.

II. Related Work

The concept of seamless handoff between different wireless interfaces has been explored in a number of contexts. Network layer approaches typically assume an IP stack for all interfaces, and try to preserve IP connectivity as hosts move [1], [2], [3], [4], [5], [6], [7]. Session layer approaches operate above the transport layer, while still making radio switching transparent to the application layer [8], [9], [10], [11], [12], [13], [14].

1-4244-2575-4/08/$20.00 ©2008 IEEE

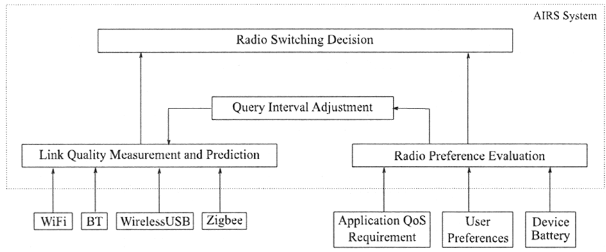


Fig. 1. AIRS System

Switching at the session layer enables devices to utilize many different types of radios. However, much of the work in this area is very preliminary, with many problems not yet addressed.

Several decision algorithms have been developed for deciding when to perform a handover or which interface to use for a particular flow. Singh et al. describe how to optimally assign flows to different access networks, assuming that all interfaces are always available, but characterized by variable delay and bit rate [14]. Wang et al. describe a handoff system that allows users to express policy about what is the "best" wireless system at the current moment, with the goal of balancing network load among networks with similar performance [15]. Handoffs are only performed if the network has been consistently available for some time. Chen et al. propose a vertical handoff decision making scheme using a score function on three criteria: expense, link capacity, and power consumption [8]. A few projects have proposed decision algorithms based on fuzzy logic and neural networks [3], [16], [17]. Much of this work reacts to current network conditions, rather than predicting future availability.

III. Radio Switching Decision Algorithm

Our decision algorithm is part of a larger Autonomous and Intelligent Radio Switching (AIRS) system [18]. The goal of this system is to leverage radio diversity and keep the user connected to available network services using the "best" available interface at any given moment.

As illustrated in Figure 1, the AIRS system is composed of four key modules. The *Radio Preference Evaluation* module dynamically maintains an ordered preference list for each of the wireless interfaces, based on user preference, the application's QoS requirement, and the current status of the device's battery [19]. This module allows the user to select one of three profiles: "high throughput", "power efficient", and "adaptive". The latter choice optimizes for throughput when battery power is high, then gradually switches to more power efficient interfaces as battery power starts to decrease. The *Link Quality Measurement and Prediction* module uses periodic measurements of each interface to predict the availability and quality of each radio in the near future [20]. The *Query Interval Adjustment* module adjusts how frequently queries are made, based on the past performance of the interface and its placement in the preference list.

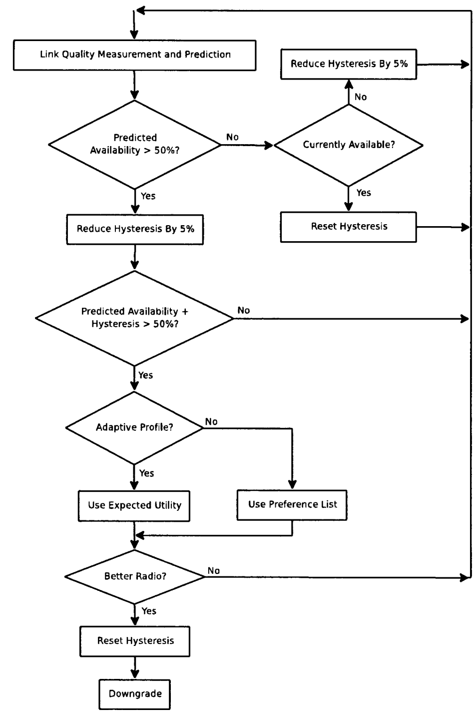


Fig. 2. Downgrade Decision Algorithm

In this paper, our focus is on the *Radio Switching Decision* module, which determines which radio should be used and when the handoff should be made to this radio. This module takes into consideration the predicted quality of each interface as well as the ordered preference list. The prediction, $P_{avail}(R_i)$ is given as a percentage chance that the radio for interface i will meet application QoS requirements in the near future. In AIRS the prediction must be greater than 50% in order for the system to consider that link to be available, and thus eligible to be chosen by the decision module.

The decision module makes a distinction between two types of radio switching. An *upgrade* occurs when a more desirable radio becomes available and the active interface is superseded. A *downgrade* occurs when the active connection becomes unavailable and the connection must switch to a less desirable radio.

A. Downgrade Switching

Figure 2 shows the decision algorithm for a downgrade; this algorithm is executed whenever the AIRS system receives a new periodic link measurement (and hence a new availability prediction) for the active radio, R_a, that is currently being used by a connection.

At the start of this algorithm, a hysteresis parameter, h_a, for the interface is initialized to a positive value, e.g. 15%. The initial value of the hysteresis parameter determines how badly a link may perform before the system will downgrade. By initializing this to, for example, 15%, the system allows a link's predicted availability to reach 35% before a downgrade takes place. The hysteresis decreases when a link is currently unavailable, so that the system can react more quickly when a radio suddenly cannot be used. We later use simulations to determine a good initial value for this parameter.

The first step in the algorithm is to determine whether the current radio is predicted to be available in the near future; this is true if $P_{avail}(R_a)$ is greater than 50%. If the radio will be available, the algorithm next checks whether the current measurement indicates the link is available right now. This is necessary because the predicted availability is based on many previous measurements, whereas the current availability is based on only the most recent measurement. A link may have a long history of availability, then suddenly become unavailable (e.g. due to mobility) or may suffer transient interference, which should be ignored. The challenge is to adapt quickly to changes in link status while remaining stable during periods of transient interference.

To handle this uncertainty, our decision algorithm relies on a combination of predicted availability, plus hysteresis. If the active radio is not currently available, h_a is reduced by 5%, otherwise it is reset to its initial value. If, in the original step, the link is predicted not to be available in the future, then h_a is reduced by 5% and a new check is made by determining whether $P_{avail}(R_a) + h_a$ is greater than 50%. If the interface is not available by this measure, then a downgrade is initiated.

To initiate the downgrade, the decision module first selects the best available interface. If the user has selected the "adaptive" profile, the preferred interface is the one with the highest expected utility, $U_{expected}(R_i)$, calculated as:

$$U_{expected}(R_i) = U_{social}(R_i) \times P_{avail}(R_i) \quad (1)$$

The social utility is derived from user preference on the two communicating devices and the the characteristics of the link, such as delay and bandwidth. If the user instead prefers to optimize throughput or power consumption exclusively, then the best available interface is selected from an ordered preference list. Once a new radio is selected, algorithm resets h_a for the active radio and switches to the new radio.

B. Upgrade Switching

Figure 3 shows the decision algorithm for an upgrade, which is executed whenever the AIRS system receives a periodic link measurement and prediction for an inactive radio, R_i. At the start of this algorithm, a link verification parameter, v_i, for the interface is initialized to a positive value, e.g. 4. This parameter indicates how many additional measurements must be taken before the interface is considered as a candidate for an upgrade switch. Thus a value of 4 would indicate that the link must be available for four consecutive measurement periods before it is used.

The first step in the algorithm is to determine whether this (inactive) radio is available. If it is available, the algorithm next checks whether this radio has a higher expected utility, or higher preference ranking, than the current radio. If this interface is preferred, v_i is decreased by 1. Once v_i reaches zero, this link may be used for an upgrade switch.

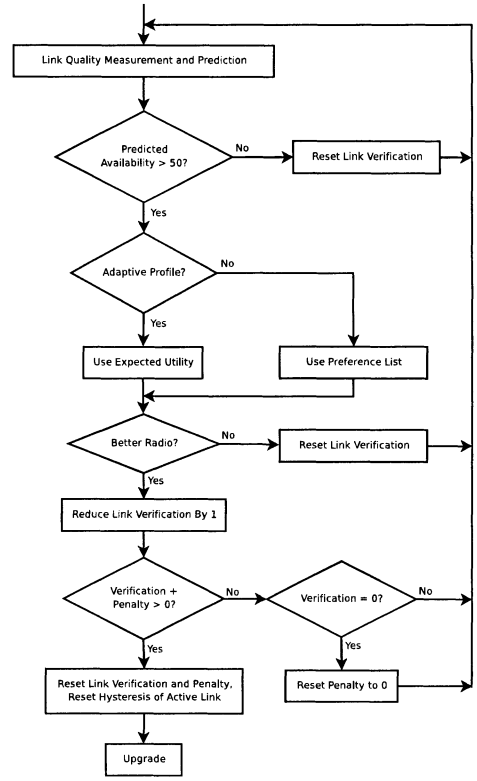


Fig. 3. Upgrade Decision Algorithm

The decision algorithm also uses a penalty parameter, p_i, to avoid radios that have failed previously. This parameter is set to one if the radio becomes unavailable within 3 seconds after it was used for an upgrade. It is reset back to zero once the radio has been available again for a consecutive number of measurements (equal to the initial value of v_i). If both v_i and p_i reach zero, and this radio is the most preferred available radio, then an upgrade is initiated.

We later use simulations to determine a good initial value for the link verification parameter.

IV. Performance Evaluation

We perform a simulation study using ns-2.28 to calibrate the radio switching decision algorithm's parameters and to evaluate its effectiveness. Our simulation implements the entire AIRS system, since the decision module depends on input from both the prediction module and the preference module.

As mentioned earlier, we decompose the radio switching problem to a negotiation between adjacent devices. Our topology thus consists of two adjacent mobile devices, each with WiFi, Bluetooth, WirelessUSB, and ZigBee radios. The two devices use a VoIP application running over UDP, though the choice of application and transport protocol does not affect our results. In addition, our topology includes 10 pairs of Bluetooth devices and 10 pairs of WiFi devices. In our experiments, we use mobility, plus interference from the additional devices, to vary the channel quality for each of the radios.

To evaluate the effectiveness of our decision algorithm, we measure the *average switch latency*. For a downgrade, this is the difference between the time when the active radio becomes unavailable and when the downgrade switch occurs. For an upgrade, this is the difference between the time when the switch occurs and the time when the new radio becomes available. Of course, a naive decision algorithm could immediately switch to a different radio whenever the current one becomes unavailable or a better one becomes available. Thus latency must be balanced by the need to eliminate frequent switches. We consider a frequent switch to be one that occurs within 3 seconds of the last switch; we report the *frequent switches* as a percentage of the total switches. We also measure *goodput* and *battery power* to determine the effect of radio switching on application performance.

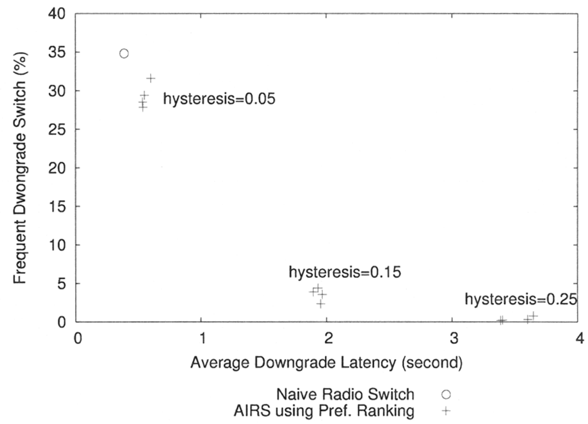


Fig. 4. Downgrade Switching Hysteresis Tradeoff

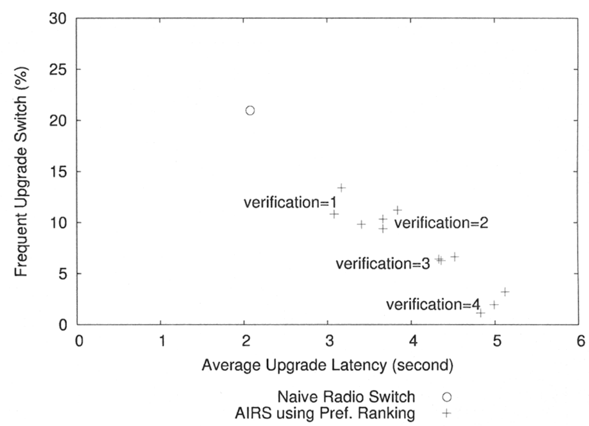


Fig. 5. Upgrade Switching Link Verification Tradeoff

A. Decision Algorithm Parameters

We perform a variety of simulations with different scenarios to determine the proper settings for the hysteresis and link verification parameters. In selecting scenarios for these experiments, our goal is to have enough variation in radio availability so that the switching model parameters we choose will work across a wide range of possible situations. Accordingly, we use scenarios that include times when the radio is continuously available, times of periodic unavailability, and times of high volatility. We also use both the high throughput and power efficient user profiles, with preference ranking as the selection criteria.

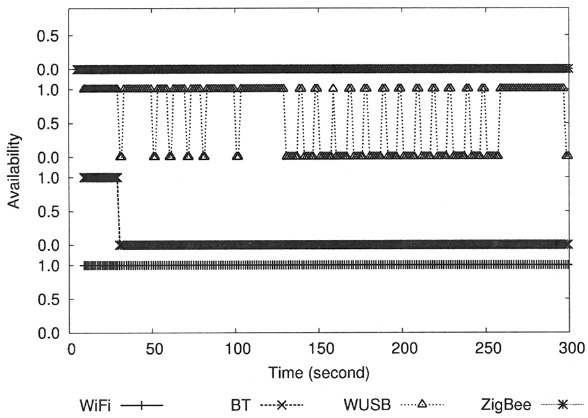
In all cases, we generate the simulation scenarios randomly, run each simulation for 300 seconds, and average our results over 50 replications. We use a typical battery life for PDAs, 10 watt-hours. We compare the AIRS decision algorithm to a naive radio switching algorithm that uses the same prediction inputs, but switches as soon as possible whenever a better radio is available.

For downgrades, there is a clear tradeoff between the average switch latency and frequent switches, as shown in Figure 4. Each symbol on the graph represents a different combination of the hysteresis parameter (ranging from 0.05 to 0.25) and the link verification parameter (ranging from 1 to 4). The points that represent the same hysteresis setting cluster together, since the link verification parameter does not affect downgrade switching. With just 15% hysteresis, the percentage of frequent switches decreases to less than 5%, while the average switch latency increases from about a half a second to 2 seconds. More hysteresis can nearly eliminate frequent switches, but at the cost of another second and a half of latency. This tradeoff is clearly better than the naive algorithm, which switches quickly but frequently. Based on this evaluation, we use 15% for this parameter in the remaining simulations.

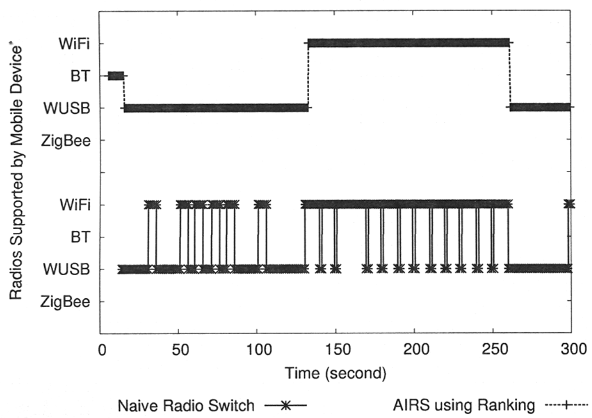
A similar tradeoff exists for upgrades and the link verification parameter, shown in Figure 5. The number of frequent switches decreases and the latency increases as the verification parameter increases, and a setting of at least 4 reduces the percentage of frequent switches to below 5% again. The naive algorithm is again limited to frequent but fast switches. In the case of upgrade switching, an active radio is already being used, so it is less critical to have low latency in this situation than for a downgrade. We thus use a setting of 4 for the link verification parameter in the remaining simulations.

To illustrate how effective the decision algorithm can be in avoiding frequent switches, we run an additional experiment that causes frequent disruptions in the availability of one of the radios. Figure 6(a) shows the measured availability for each radio on the two devices. The radios are shown from bottom to top in order of highest power consumption to lowest power consumption. The WiFi radio is always available; the Bluetooth radio is available at first, but then drops off; the WirelessUSB radio is volatile; and the ZigBee radio is always unavailable.

The important part of this scenario is that, for the power efficient user profile, the WirelessUSB radio is the most preferred radio, since the ZigBee radio is always unavailable. There is one period where WirelessUSB is mostly available, with spikes where it is ineffective, and another period where it is mostly available, with spikes of activity. These periods are



(a) Radio Availability



(b) Radio Switching

Fig. 6. Handling Volatility

caused by the radio moving in and out of range, or perhaps by interference.

In this scenario, as shown in Figure 6(b), the naive algorithm switches very frequently, which can cause interruptions in the conversation and additional overhead. The AIRS decision algorithm, however, allows for much more stable selection of radios, using lower powered options when they are mostly available, and switching to WiFi only when necessary.

B. Performance Comparison

We evaluate the AIRS decision algorithm by comparing it to several alternative algorithms. The naive switching algorithm, discussed previously, switches whenever there is a more preferred radio available, and uses the AIRS prediction module to determine availability. The packet loss algorithm switches to the next best radio whenever a single link-layer frame is lost using the current radio. The timeout algorithm switches to the next best radio whenever the transport layer times out (about 10 seconds). Each of these algorithms use preference lists, so we test them using both the high throughput and power efficient user profiles.

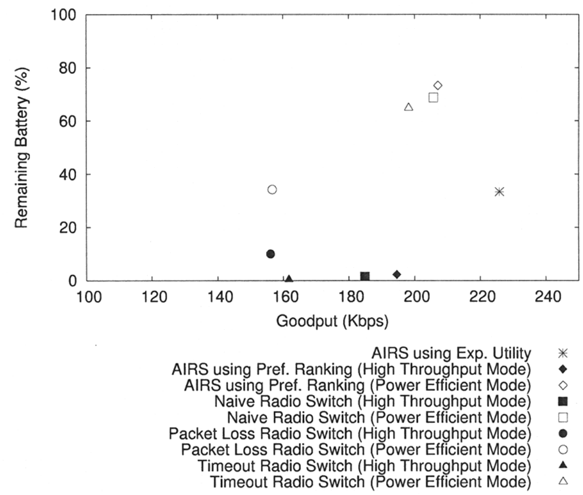


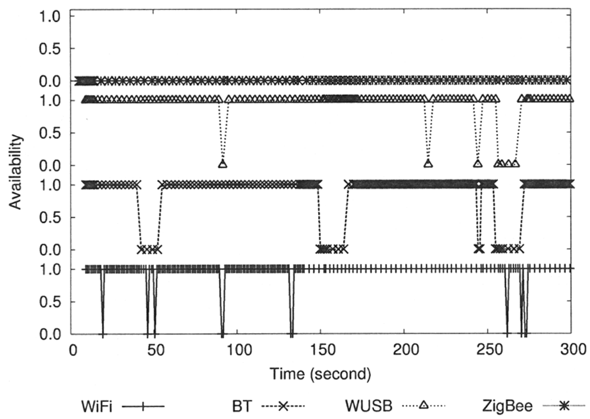
Fig. 7. Goodput and Battery Life Tradeoff

We generate simulation scenarios randomly, including periods of interference and availability to affect the different radios. Our scenarios use parameters that give a high likelihood that there is at least one radio available at all times. Device battery life is randomly chosen in the range 35 - 65 watt-hours; at the low end of this range the battery is not sufficient to use the highest powered radio for the duration of the simulation. Each simulation runs for 300 seconds and we average results over 50 replications.

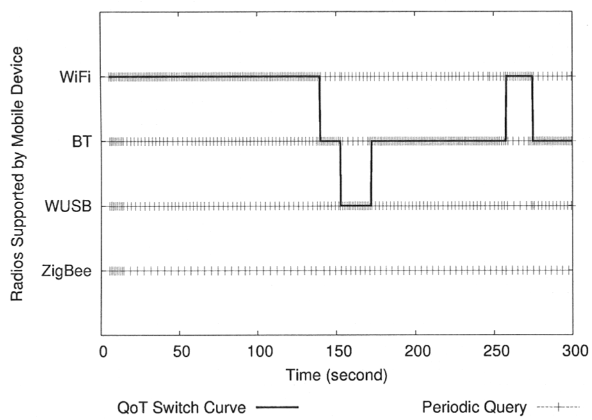
As shown in Figure 7, the AIRS system provides the best tradeoff between battery power and goodput. The scenarios for the high throughput profile are clustered on the bottom of the graph. In each case, the power of the device is nearly depleted, but the AIRS algorithm gets the most goodput. Likewise, the scenarios for the power efficient profile are clustered near the top of the graph. Most of these actually get higher goodput, plus longer battery life, because there are radios that provide good enough throughput while consuming less power. The AIRS system again does the best of these. Finally, the AIRS system using the adaptive profile gets the most goodput, while still preserving much of the battery. This shows that the adaptive profile, along with expected utility in the decision algorithm, is a good choice for balancing these two objectives.

To illustrate how AIRS works when using the adaptive profile, we randomly selected one simulation and show how the system dynamically chooses a radio over time to balance power and throughput. Figure 8(a) shows the measured availability for each radio on the two devices, with WiFi, Bluetooth, WirelessUSB, and ZigBee from top to bottom.

Figure 8(b) shows how the AIRS system changes the active radio over time, using the adaptive profile. Initially the system uses WiFi, since it offers the highest throughput and the battery power is high. As the battery becomes depleted, it switches to Bluetooth, then WirelessUSB when Bluetooth is unavailable for a short period of time. It then continues to use Bluetooth



(a) Radio Availability



(b) Radio Switching

Fig. 8. AIRS Radio Switching Scenario

to preserve battery power, except for a short period near the end where it must switch to WiFi to maintain connectivity.

V. Conclusion and Future Work

The AIRS system is a key component of a heterogeneous wireless network. For any pair of communicating nodes, the system is able to dynamically choose the best available radio, while balancing throughput and power. The system uses several mechanisms to avoid frequent switching, and offers the user the choice of three different performance profiles.

A number of areas remain for future work. In a wireless network with many systems using AIRS simultaneously, additional mechanisms may be needed to provide stability and ensure that the network-wide utility is optimized. In addition, an implementation of AIRS would provide valuable insight into its feasibility and performance.

References

[1] M. Stemm and R. H. Katz, "Vertical handoffs in wireless overlay networks," *Mobile Networks and Applications*, vol. 4, 1999.

[2] M. Baker, X. Zhao, and J. Stone, "Supporting mobility in mosquitonet," in *USENIX Technical Conference, San Diego, California*, 1996.

[3] W. Zhang, "Handover decision using fuzzy MADM in heterogeneous networks," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2004.

[4] J. Ylitalo, T. Jokikyyny, T. Kauppinen, A. J. Tuominen, and J. Laine, "Dynamic network interface selection in multihomed mobile hosts," in *36th Hawaii International Conference on System Sciences (HICSS)*. IEEE, 2002.

[5] M. Ylianttila, R. Pichna, J. Vallstrom, J. Makela, A. Zuhedi', P. Krishnamurthy, and K. Pahlavan, "Handoff procedure for heterogeneous wireless networks," in *Global Telecommunications Conference (Globecom)*. IEEE, 1999.

[6] J. Tourrilhes and C. Carter, "P-handoff: A protocol for fine grained peer-to-peer vertical handoff," in *The 13th IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications*. IEEE, 2002.

[7] P. Rodriguez, R. Chakravorty, I. Pratt, and S. Banerjee, "Mar: A commuter router infrastructure for the mobile internet," in *ACM MOBISYS*, June 2004.

[8] L.-J. Chen, T. Sun, B. Chen, V. Rajendran, and M. Gerla, "A smart decision model for vertical handoff," in *The 4th ANWIRE International Workshop on Wireless Internet and Reconfigurability (ANWIRE)*, 2004.

[9] N. Venkitaraman, J. Almaula, A. Haneef, and J. Mysore, "Session aware network controlled interface selection for multi-homed hosts," in *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, 2004.

[10] S. Giordano, D. Lenzarini, A. Puiatti, and S. Vanini, "Wiswitch: Seamless handover between multi-provider networks," in *International Conference on Wireless on Demand Network Systems and Service (WONS)*. IEEE, Jan. 2005.

[11] S. Giordano, M. Kulig, D. Lenzarini, A. Puiatti, F. Schwitter, and S. Vanini, "Wioptimo: Optimised seamless handover," in *Wireless Personal Multimedia Communications (WPMC)*. IWS, 2005.

[12] S. Giordano, D. Lenzarini, and A. Puiatti, "Demonstrating seamless handover of multihop networks," in *REALMAN*. ACM, 2006.

[13] G. A. D. Caro, S. Giordano, M. Kulig, D. Lenzarini, A. Puiatti, and F. Schwitter, "A cross-layering and autonomic approach to optimized seamless handover," in *International Conference on Wireless on Demand Network Systems and Service (WONS)*. IEEE, 2006.

[14] J. P. Singh, T. Alpcan, P. Agrawal, and V. Sharma, "An optimal flow assignment framework for heterogeneous network access," in *the proceedings of IEEE Int. Symp. on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, June 2007.

[15] H. J. Wang, R. H. Katz, and J. Giese, "Policy-enabled handoffs across heterogeneous wireless networks," in *Second IEEE Workshop on Mobile Computing Systems and Applications (WMCSA '99)*. IEEE, 1999.

[16] B. Hongyan, H. Chen, and J. Lingge, "Intelligent signal processing of mobility management for heterogeneous networks," in *International Conference on Neural Networks and Signal Processing*, vol. 2. IEEE, Dec. 2003, pp. 1578 – 1581.

[17] N. D. Tripathi, J. H. Reed, and H. F. V. Landingham, "Pattern classification based handoff using fuzzy logic and neural nets," in *International Conference on Communications (ICC)*. IEEE, June 1998, pp. 1733–1737.

[18] C. D. Knutson, H. R. Duffin, J. M. Brown, S. B. Barnes, and R. W. Woodings, "Dynamic autonomous transport selection in heterogeneous wireless environments," in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, 2004.

[19] Q. Duan, L. Wang, C. D. Knutson, and M. A. Goodrich, "Axiomatic multi-transport bargaining: A quantitative method for dynamic transport selection in heterogeneous multi-transport wireless environments," in *IEEE WCNC*, 2006.

[20] Q. Duan, L. Wang, C. D. Knutson, and D. Zappala, "Link quality prediction for wireless devices with multiple radios," in *Proceedings of IEEE International Symposium on a World of Wireless Mobile and Multimedia Networks*. IEEE, June, 2008.