Exploiting radio hierarchies for power-efficient wireless device discovery and connection setup

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Abstract

We propose the coordinated use of multiple heterogeneous wireless technologies to optimize the latency and power consumption of mobile systems during device discovery and connection setup. We present several multi-radio connection establishment techniques, which exploit the wide disparity in the power and performance characteristics of different radios to create an efficient and flexible communication subsystem. Our techniques enable mobile devices to combine the strengths of these diverse technologies, thereby powering down higher power radios when their capabilities are not needed and using a hierarchical radio structure for device discovery and connection setup. Experiments using a prototype multi-radio device show that the use of radio hierarchies results in significant power savings, and often improves connection setup latency as well.

1. Introduction

Combining multiple wireless technologies into a single mobile device enables the creation of an efficient hierarchical communication subsystem that is performance- and energy-scalable. Since different wireless technologies have vastly differing bandwidth and power consumption characteristics, a multi-radio system can traverse the power-bandwidth tradeoff curve by judiciously choosing which radio is used at any given time. This paper presents techniques to realize the benefits of such hierarchical radio systems in the context of wireless device discovery and connection setup. Using our scheme, higher-level radios are turned off during quiescent operation, and a lower power radio is used to discover nearby devices. Unlike existing schemes that use a secondary radio purely for paging purposes, our technique uses the lower-level radio to discover, appropriately configure, and activate a higher-level radio link when an active connection is desired.

Power consumption and discovery/connection latency are our primary evaluation metrics. Battery life considerations mandate that the device consume minimal power in its quiescent (idle) state and latency is important as it affects the user experience during device discovery and connection setup. Further, since these metrics are inter-dependent (*e.g.*, it is possible to save power by increasing discovery latency), they need to be considered jointly while optimizing the connection setup procedure, to fully understand the associated tradeoffs.

1.1. Paper contributions

This paper proposes the use of radio hierarchies for power-efficient wireless communication, and demonstrates their benefits in the context of wireless device discovery and connection setup. We present several hierarchical connection setup techniques and evaluate them using a prototype multi-radio wireless platform. Experimental results demonstrate that radio hierarchies can significantly reduce power consumption (up to 40x) while supporting "always on" radio connection models. The various issues involved in the design and use of hierarchical radio systems are also discussed.

1.2. Motivation and the radio hierarchy concept

Numerous wireless communication technologies are in use today, such as Wi-Fi (IEEE 802.11 a/b/g), Bluetooth, IrDA, UWB, RFID, IEEE 802.15.4, *etc*. In order to ensure seamless connectivity while roaming between locations that support different wireless technologies, several mobile devices including laptops, PDAs, and cell-phones are beginning to be equipped with multiple wireless interfaces. Figure 1 shows one such wireless platform that we have built [1], which supports the simultaneous operation of three different radios (Wi-Fi [2], Bluetooth [3], and the Chipcon CC1000 [4]). This "convergence" of radio technologies onto a single system has significant implications for system and network designers.

Even in single radio wireless devices, the communication subsystem is responsible for a large portion of the system's total power budget [5]. Adding additional wireless interfaces to a device only makes the communication subsystem even more dominant. Power profiling of our multi-radio system corroborates the fact that the radios are, by far, the dominant power consumers (together accounting for 70% of total power consumption in active mode) [6].

Our radio-hierarchy approach to communication power management aims to improve the match between radio characteristics and application requirements. For example, Bluetooth radios are highly optimized for low-power operation and transmission of small amounts of data, while Wi-Fi is more efficient for bulk data transfer and high-bandwidth communication. It is only natural that the wireless subsystem adapts itself by seamlessly transitioning from one radio to another as the device's communication requirements change over time. Further, since multiple radios already exist in many commercially available devices, it makes sense to exploit this capability to improve system performance, especially since the cost of adding a second radio, although often insignificant, is eliminated altogether in these systems.

Note that the basic concept of hierarchical radios is by no means limited to device discovery. Radio hierarchies offer the potential for power savings in several other scenarios, including active data transfer. For example, depending on the instantaneous bandwidth requirement or observed noise and interference levels, active data connections can be seamlessly migrated from one radio channel to another to improve energy efficiency. We plan to study these other possible uses of radio hierarchies as part of our future work.

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1.3. Usage models and other issues

The radio hierarchy concept supports truly mobile and ubiquitous usage models where a device moves between un-coordinated wireless domains. For example, consider a scenario where a user walks up to a point-of-sale music kiosk to download a new song to their mobile device. If the wireless subsystem were turned off, the user would have to manually turn it on when they know they are near a kiosk and wait for it to discover and connect to the kiosk infrastructure. Alternatively, the mobile device could continually scan the environment for nearby kiosks or access points (APs), enabling automatic transactions with the infrastructure, but increasing the device's power drain. Using radio hierarchies decreases this power overhead while retaining the rich user experience offered by the automatic transaction model.

A potential challenge to the use of radio hierarchies is the range disparity between the different radios. For example, the range of Bluetooth is around 30 feet, which is far lower than the range of Wi-Fi. However, for many emerging usage models, such as downloading music from a point-of-sale kiosk, this will not be an issue since the user will often be in close proximity to the AP. As another example, consider a café or apartment that is only 50 feet across. Here too, the range of Bluetooth is sufficient for device discovery and the Wi-Fi channel can be thought of as augmenting the Bluetooth link by providing an "on-demand" high bandwidth channel for data transfer. Alternatively, one can think of Bluetooth as a low-power augmentation to more conventional Wi-Fi usage models. In these cases, it is possible to increase the effective range of a technology such as Bluetooth by (i) using multiple Bluetooth APs for each Wi-Fi AP, (ii) using a power amplifier (subject to any government regulations on transmit power), or (iii) specialized antenna design on the base station. Also, the device discovery algorithm can always revert back to the conventional Wi-Fi based discovery if no Bluetooth beacons are heard for a certain time, possibly due to being out of range. In this case, the advantages of using the radio hierarchy are realized only at certain times, and the system behaves as a conventional single-radio device at other times.

An important aspect of the connection process is selecting which AP to connect to. Wi-Fi uses a default policy of connecting to the AP within a specified service set that has the maximum received signal strength at the mobile device. However, this does not work when APs belong to different service providers. A possible approach could be to connect only to APs of a particular ISP for which the user has a paid subscription, or APs that are advertised as being for public use (through a field in the beacon packet). This can be incorporated into our hierarchical radio technique by communicating the relevant information (such as provider ID) in the associated out-of-band channel.

2. Related Work

There are two main areas of related work, namely exploiting multi-radio systems for roaming between wireless networks, and using paging channels for power management.

Vertical handoff [7], [8] enables the transition of active connections between local- and wide- area networks. The system supports migration of active connections, and does not address the issue of discovering new networks, which is the focus of our work. Wake-on-Wireless [9] augments a wireless handheld with a second low-power radio. The primary radio and handheld are turned off during idle periods, and woken up by a wakeup signal sent on the low-power radio channel when there is traffic intended for the sleeping device. In this scheme, the mobile device must register with the infrastructure before entering the low-power mode, which is not required by our technique. Further, our system not only offers the benefit of a low-power wakeup channel, but also uses the alternate wireless channel to communicate configuration information for aiding the connection setup process. A similar approach has been explored in [10] where IrDA is used to transfer connection information about nearby Wi-Fi APs in order to simplify the configuration process. Similarly, [11] explores using laser-based discovery for secure connections to an AP. All these technologies utilize a constrained channel, requiring line-of-sight for device discovery, and do not investigate the performance/power tradeoffs that radio hierarchies enable. Contact Networking [12] presents a software infrastructure for providing transparent mobility to a device with multiple network interfaces. It can be used to manage the protocol stack in the implementation of our hierarchical radio schemes. Finally, [13] analyzes power related tradeoffs while using multiple wireless network interfaces for active data transfer.

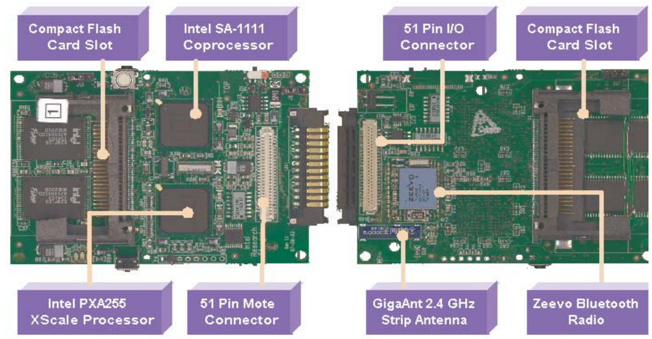


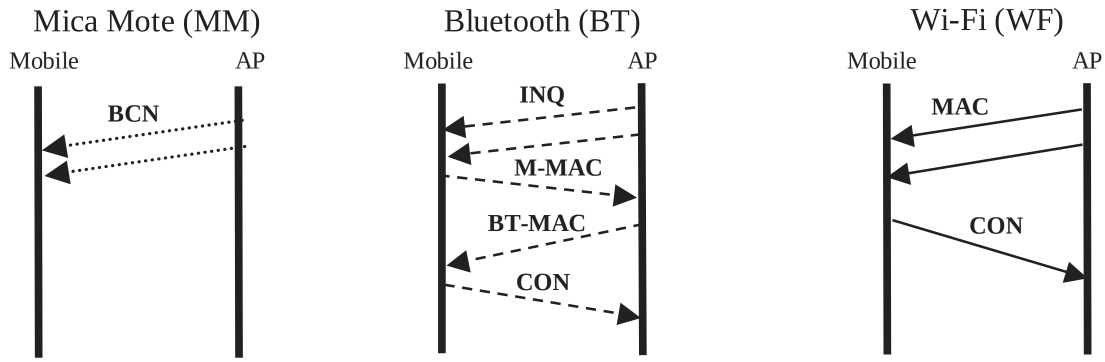
Figure 1. Our multi-radio wireless platform. The topside of the board is shown on the left and the bottom side on the right.

3. Individual Radio Profiles

Each of the radio technologies we use has a different discovery and connection procedure, which is shown in Figure 2 and discussed below.

3.1. Chipcon CC1000 (Mica2 Mote)

The lowest level of our radio hierarchy is the Mica2 Mote [14], which uses the Chipcon CC1000 RF transceiver running either in the 433 MHz or the 916 MHz band. It supports data rates of up to 76.8 kbps, and employs Carrier Sense Multiple Access based medium access. The Mote uses connectionless wireless communication: it sends data to another Mote by just using the recipient's unique address, or a broadcast address, in the destination field of the packet header. This eliminates the connection establishment overhead, which might be significant if the amount of data to be transferred is small. The Mote is a low power device, and consumes around 43mW while transmitting data. It can be put into a shutdown



The AP periodically broadcasts information to the mobile device. With this radio, no connection is formed, so the mobile device does not send any information back. In a radio hierarchy, this information is used to configure a higher-level radio subsystem.

The AP sends a stream of Inquiry packets to potential nearby receivers listening occasionally. The mobile device replies with its MAC address. The AP then pushes its MAC address to the mobile, which uses that to then form an IP-level connection to the AP, if desired.

The AP periodically beacons its configuration information on a specified channel. The mobile uses this information to appropriately configure its wireless subsystem and forms a connection to the AP by authenticating and associating with it.

Figure 2. Connection mechanisms for the three individual radios. Initially, each radio repeatedly broadcasts its information, without any specific target receiver, represented by the double lines at the beginning.

mode consuming less than 0.03mW. The latency to enter and exit the shutdown mode is insignificant. The Mote runs the TinyOS operating system that uses a default packet size of 36 bytes. The average time to transmit a packet from one Mote to another is 75ms (when there is little or no interfering Mote traffic), which includes protocol processing, random back off, and transmission delays. Thus, the Mote provides a low-power wireless channel that can be used for efficient transmission of small data packets.

3.2. Bluetooth

Bluetooth was developed for short-range, moderate bandwidth communication. The physical layer of Bluetooth is based on frequency hopping in the 2.4 GHz ISM band, and the base band operates at 1.2Mbps. Bluetooth communication is connection oriented, whereby a device has to search for nearby devices, and explicitly connect to the device it wants to communicate with, before transferring any data.

To discover nearby peers, a device sends out a sequence of *Inquiry* packets. Other devices reply with an *Inquiry Response* packet containing their MAC address, clock offset, and device type. While the clock offset is not necessary to form a connection, it helps speed up the rest of the connection process. Thus, if the target MAC address can be acquired through other means, the Inquiry process can be bypassed. To form a connection, the local device sends a series of *Page* packets addressed to the target device, which replies with a *Page-Response* packet, synchronizing the hopping sequences of the two devices and completing the connection setup.

Listening for Inquiry and Page packets is highly duty cycled, typically using a 1.3s or 2.6s time period, which makes it very low power. In contrast, transmitting a sequence of Inquiry or Page packets is significantly more power-hungry. Therefore, in our design, the AP initiates the Inquiry. This is the inverse of the conventional method where the mobile device initiates Inquiry and discovers other nearby devices, *e.g.,* wireless headset or AP. This role reversal increases connection latency since the AP must form a connection to the mobile device, push its MAC address, and then disconnect, before the mobile device can initiate a data connection. The higher latency is the price paid for avoiding the power-hungry Inquiry procedure on the mobile device. Note that data transfer can conceivably take place when the AP connects to the mobile device to push its MAC address. However, in our work, in order to retain simplicity and avoid a subsequent master-slave role switch, the AP disconnects after pushing its MAC address to the mobile device.

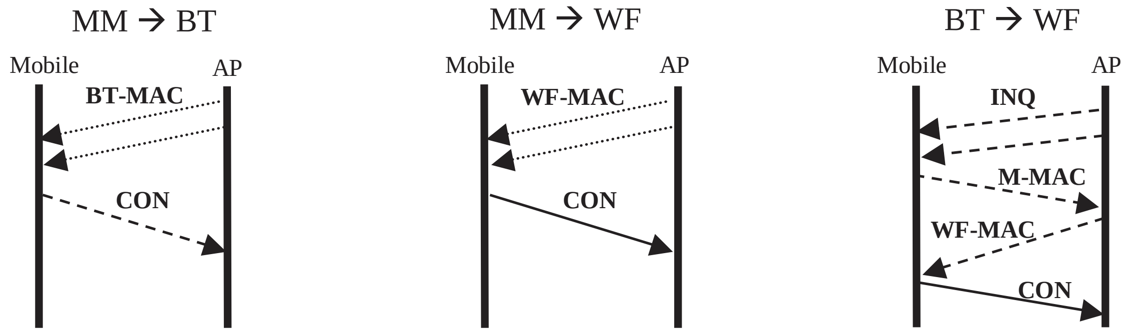
3.3. Wi-Fi (IEEE 802.11b)

Wi-Fi is the technology of choice for wireless local-area networking since it provides up to 11Mbps bandwidth. However, Wi-Fi network interface cards consume a lot of power (~1.2W in transmit mode, and ~1W in receive mode). A Wi-Fi network can exist on one of twelve predefined frequency channels, and can operate either in an AP-assisted infrastructure mode, or in a peer-to-peer ad-hoc mode.

Similar to Bluetooth, communication using Wi-Fi is connection oriented. The connection procedure consists of two phases. The first phase involves the mobile device sequentially scanning all the channels to detect the presence of nearby APs that periodically broadcast beacon packets. Once the list of APs is collected and the AP to which a connection is to be formed is identified, the second phase consists of the mobile device authenticating itself to the AP and associating with it, as illustrated in Figure 2. It has been shown that the discovery phase dominates the latency of the entire connection procedure [15]. Here too, if the configuration information of the AP (*e.g.,* BSSID, channel, WEP encryption key) can be obtained through other means, the scanning phase can be skipped altogether, resulting in significantly less connection time and power consumption.

4. Dual-Radio Hierarchies

Using the wireless technologies described in Section 3, we propose three dual-radio pathways for device discovery and connection setup, which are depicted in Figure 3. Each dual-radio scheme uses the lower-level radio channel to discover, configure, and activate the higher-level radio subsystem.



The AP broadcasts its Bluetooth MAC address using the Mote channel. When the mobile wishes to form a connection, it can directly contact the AP without performing Bluetooth inquiry.

The AP broadcasts its Wi-Fi configuration information using the Mote channel. When the mobile wishes to form a connection, it can simply enable its Wi-Fi interface, set the appropriate interface parameters and connect.

The AP queries the environment using BT protocols for nearby mobile devices. Upon finding one, it pushes the requisite Wi-Fi configuration information to the mobile host.

Figure 3. Three multi-radio connection techniques. Different line types (dotted, dashed, solid) represent the different radios, as used in the single-radio diagram.

Note that the complexity of each dual-radio connection establishment mechanism, does not necessarily increase significantly over the corresponding single-radio case due to the overlap in the functions performed by the respective radio channels (*e.g.*, in the MM→WF case, the periodic beacon transmission on the Mote channel is *in lieu of*, and *not in addition to*, the beacon transmission on the Wi-Fi channel). Also, the three-level Mote → Bluetooth → Wi-Fi hierarchy is not particularly needed for device discovery because the union of the Mote → Bluetooth and the Mote → Wi-Fi cases provides the same effect. For each technique, the decision of when, if ever, to form a connection can be dictated by user-level connection policies. For example, the device may not want to connect if the AP does not represent a free service. Similarly, if the currently running applications do not require the bandwidth offered by the higher-level radios, it may be beneficial to continue with the lower-level radio connection.

4.1. Mote → Bluetooth

In this dual-radio scheme, the Bluetooth MAC address of the AP is periodically broadcast over the Mote radio, and is used by the mobile device that performs device discovery. In essence, this technique replaces the high-latency Bluetooth Inquiry process with a simple broadcast by the Mica Mote. As mentioned previously, the Bluetooth clock offset, which is not communicated by this technique, is not necessary for connection establishment and only serves to speed up the rest of the connection setup procedure. However, even without the clock offset information, the total latency is still reduced using this scheme since the entire Inquiry process is bypassed.

4.2. Mote → Wi-Fi

This scheme replaces the periodic Wi-Fi beacon with a Mote broadcast, allowing the Wi-Fi receiver to be turned off until an active connection is desired. Wi-Fi based discovery takes significant time since it involves a traversal of all the twelve frequency channels. By replacing Wi-Fi scanning with a simple Mote beacon, this configuration saves considerable power and latency. The Mote beacon contains the ESSID and MAC address of the Wi-Fi AP, which are sufficient to form a Wi-Fi connection. Once the AP configuration information is known, this scheme has low connection latency, since Wi-Fi authentication and association do not take much time.

4.3. Bluetooth → Wi-Fi

Conceptually, the Bluetooth → Wi-Fi connection process is similar to the Bluetooth connection process, but pushes the AP's Wi-Fi configuration information instead, and performs the final connection request over the Wi-Fi channel. The Bluetooth → Wi-Fi configuration consumes considerably lower power than the Wi-Fi only solution, but has increased latency due to the lengthy Bluetooth connection process. The connection time after obtaining the AP's Wi-Fi configuration information is low because it only requires Wi-Fi authentication and association. A significant advantage of this scheme is that both Bluetooth and Wi-Fi are popular industry standards: since a number of laptops and PDAs are now equipped with these radios, this technique is directly applicable to a variety of commercial devices.

5. Experimental Setup

We have created an extensive experimental setup, shown in Figure 4, to evaluate the various connection setup alternatives. The components of this setup are detailed below.

5.1. Multi-radio mobile device and access point

The mobile system used in our experiments is a prototype research platform that we have built. The device, shown in Figure 1, has an Intel XScale PXA-255 processor operating at 400 MHz, 64MB of SDRAM, and 32MB of on-board flash. It contains an on-board Bluetooth radio. There is a Compact Flash (CF) slot for the Wi-Fi radio (we used a Netgear MA701 card). The device has a customized connector that allows a Mote to be attached to it. An add-on daughter card provides Ethernet, host USB, and RS-232 support. The device runs the 2.4.19-rmk7 Linux operating system kernel for the ARM processor architecture, and features a complete TCP/IP networking protocol stack. A suitably equipped platform in the vicinity plays the role of a multi-radio AP and provides wireless "service" for each of the three technologies: a Mote beacon that broadcasts the appropriate "connect to" information, a Bluetooth module that searches for nearby

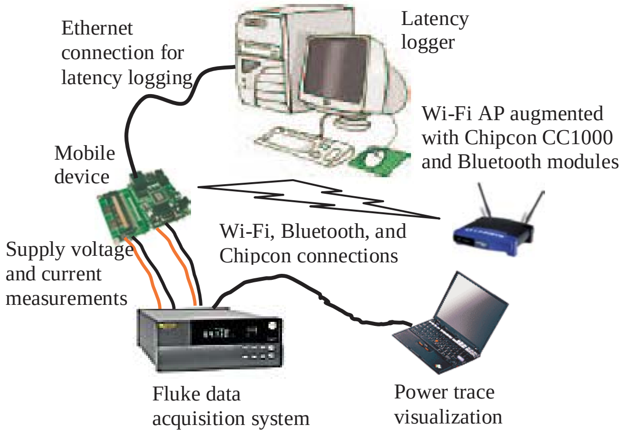


Figure 4. Experimental setup. The mobile device is wired to dedicated time and power loggers, and connects to an AP augmented with the various wireless technologies.

mobile devices that want to connect to it, and a standard Wi-Fi AP. Finally, we use the radios in a standard "out of the box" configuration and do not adjust the transmission power or other low-level parameters of the radios.

5.2. Latency measurement procedure

The latency for the entire discovery and connection setup procedure is divided into two components: the time taken to discover a new AP (referred to as the discovery latency), and the time taken to actually form a connection (referred to as the connection latency). Connection latency is the time from when the connection setup is initiated to when one IP ping packet is successfully sent and received. This includes the time taken to configure the physical interface, connect to the AP, and transmit and receive one IP packet. The AP selection process is assumed to be automated and instantaneous.

The latencies were calculated by monitoring explicit events such as "connection initiated" and "beacon received" that were generated by testing programs and time-stamped at a granularity of 1ms by a latency logger. The latency logger is a 1GHz Linux desktop PC connected to the experimental device over an Ethernet link. To eliminate any jitter in the latency logging procedure due to Ethernet traffic, the Ethernet link is part of an isolated sub-network. The logs were post-processed to compute the discovery and connection latencies, which were then averaged over 100 trial runs.

Using such an instrumented test bed makes it difficult to incorporate the effect of device mobility. Instead, we emulate this by triggering the device to suddenly begin discovery at a random instant in its duty-cycle schedule. This approximates the time instant when the mobile device enters the radio range of the AP. To accurately profile the roaming case would require physically moving the device or the AP, making it very difficult to run repeated experiments.

5.3. Power measurement procedure

The mobile device is interfaced to a multi-channel NetDAQ 2645A data acquisition system that monitors the voltage drop across current-sense resistors placed in series with the various power supplies. It collects data at 100 samples/sec, which is post-processed to generate average current values. The supply voltage to the communication subsystems is also monitored and used to generate power consumption values. The power consumption reported here is only that of the radios with the power consumption of the core mobile platform, including the processor and on-board memory subsystems, being factored out. Although the PXA-255 processor is used to pass configuration information between radio subsystems in our experiments, this is not a necessity. Since each radio system incorporates its own embedded processor, the radios could pass configuration information directly to each other if suitably connected.

Table 1. Impact of power gating on the Shutdown mode power consumption and wakeup latency of the individual radios.

Radio	Power Gating Disabled	Power Gating Enabled	Power-Enable Latency	Total Wake Up Latency
Bluetooth	58 mW	1 mW	1245 ms	1698 ms
Wi-Fi	269 mW	1 mW	102 ms	1205 ms

5.4. Power gating the individual radios

Wireless interfaces are usually power managed using the shutdown modes that the radios provide. However, due to differences in the design of radios manufactured by different vendors as well as the device drivers, this often fails to yield satisfactory power reduction. For example, the Netgear MA 701 CF Wi-Fi card that we used still draws 83mA of current in the power down mode. This translates to 269mW of power consumption even when the card is shut down, which severely impacts battery life. It is also reported in [9] that other Wi-Fi cards also consume at least 50mW in sleep mode.

We address this problem by power gating the wireless subsystem, which involves placing a power MOSFET in series with the radio's power supply. By turning off the MOSFET, power supply to the radio can be completely cut off, reducing its power consumption to almost zero. We have implemented power gating for both the Bluetooth and the Wi-Fi radios in our mobile platform. The Mote does not require power gating since it has an efficient shutdown mode.

Table 1 shows the power consumption of the Wi-Fi and Bluetooth subsystems in the "Shutdown" mode, before and after gating. Power gating the radio subsystems also involves a latency overhead, since they have to be powered up before being used. The extra latency that power gating adds to the wake up time is shown in the table. Note that the latency impact of power gating on the Wi-Fi radio is minor – most of the wake up delay is due to factors such as re-initializing the drivers and firmware. However, for the Bluetooth radio this latency is around a second, which is likely due to the specific low-level Bluetooth driver and firmware implementations.

6. Experimental Results

The results of our experiments are summarized in Table 2. Discovery power is the average power consumed while searching for nearby devices. Discovery latency is the time taken to discover and obtain configuration information of a nearby AP. Radio wake up latency is the overhead associated with powering up the higher-level radio and initializing the drivers. Connect latency is the time taken to actually form a connection to the AP. The active data-transfer characteristics of each scheme are also presented in the last three columns.

Table 2. Experimental results showing the power consumption, discovery and connection latencies, overhead of power gating, and active mode data transfer characteristics. All columns represent measured values averaged over multiple runs.

Wireless Scheme	Discovery Power	Discovery Latency	Radio Wakeup Latency	Connect Latency	Transfer Bandwidth	Transfer Power	Transfer Energy/Bit
Mica Motes (MM)	8.3 mW	457 ms	N/A	N/A	N/A	N/A	N/A
Bluetooth (BT)	60 mW	2935 ms	N/A	2477 ms	310 kb/s	145 mW	468 nJ
MM → BT	9.3 mW	457 ms	1698 ms	1293 ms	310 kb/s	145 mW	468 nJ
Wi-Fi (WF)	398 mW	1298 ms	N/A	222 ms	4584 kb/s	1049 mW	229 nJ
MM → WF	9.3 mW	457 ms	1205 ms	222 ms	4584 kb/s	1049 mW	229 nJ
BT → WF	61 mW	2935 ms	1205 ms	1985 ms	4584 kb/s	1049 mW	229 nJ

As is evident from the table, the biggest power gains come from using the Mote to perform Wi-Fi discovery, where a power reduction of more than 40x is obtained. Using a Bluetooth → Wi-Fi hierarchy also saves considerable power, but at the cost of increased latency. However, this combination is an attractive option because both Bluetooth and Wi-Fi are already available on a wide variety of mobile devices. In addition, Bluetooth provides moderate communication bandwidth, so hierarchical power management can be performed during active data transfer as well. Finally, using the Mote to assist Bluetooth discovery results in a *simultaneous* decrease in power consumption and connection latency. Note that the Bluetooth and Bluetooth → Wi-Fi schemes suffer from an increase of 1763 ms in connection latency due to the inverted Inquiry model as compared to the conventional mobile-initiated Inquiry model.

Power gating the higher-level radios increases the connection latency since they would have to be powered up first, but this overhead is worth it due to the substantial power reductions obtained. Finally, we do not duty cycle the Bluetooth or the Wi-Fi radios during device discovery. Duty-cycling the lowest level radio in a hierarchy (by turning off the radio between two successive discovery attempts) would further decrease the average power consumed during device discovery at the cost of increased discovery latency.

7. Avenues for Future Work

There are several issues that merit future investigation. First, the power consumption of some radios in idle mode is far from ideal. Improving this would require a joint optimization of the radio hardware, firmware, and OS drivers. Next, other discovery mechanisms could be implemented in addition to those considered here. For example, we have used an inverted connection model for Bluetooth, to decrease the mobile device's power drain at the cost of increased latency. For latency-critical scenarios, a mobile-initiated Bluetooth connection model may be more suitable. Also, several emerging radio technologies, such as IEEE 802.15.4, can play the role of the lower-level radio efficiently while also offering increased bandwidth for active data transfer.

It is well known that Bluetooth and Wi-Fi interfere with each other because they share the same frequency band. However, the recent Bluetooth 1.2 specification describes several interference mitigation techniques, which, if implemented, will allow the two radios to co-exist somewhat amicably. Finally, the use of radio hierarchies for active data transfer also needs to be explored.

8. Conclusions

We have demonstrated that hierarchical communication subsystems built using existing radio technologies optimize the power consumption of a mobile device during the wireless device discovery and connection setup process. By using lower capability radios to perform device discovery, high power radios can be shut down until they are needed for an active connection. Experimental results show that hierarchical radios enable up to an order of magnitude reduction in discovery power, and sometimes lead to a simultaneous decrease in connection latency as well. The Bluetooth → Wi-Fi configuration is particularly attractive since it uses radios found in many existing mobile devices and hence presents an immediately viable option for power reduction of these commercially available systems. Although the power management features of some radios are poor in existing systems, preventing us from realizing the full benefit of our techniques, we believe that, as next generation radios improve, hierarchical radio approaches will be an invaluable tool for improving the battery lifetime of wireless devices.

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