PAN-on-Demand: Building self-organizing WPANs for better power management

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Abstract

In this paper, we present PAN-on-Demand, a self-organizing multi-radio system that balances performance and energy concerns by scaling the structure of the network to match the demands of applications. Since current mobile devices ship with multiple radios, PAN-on-Demand can improve performance and extend battery lifetime by switching between different wireless interfaces such as Bluetooth and WiFi and opportunistically exploiting the available power-saving strategies. When applications are actively using the network, PAN-on-Demand offers high-bandwidth, low-latency communication; when demand is light, PAN-on-Demand adapts the network structure to minimize energy usage. Our results show that PAN-on-Demand reduces the average response time of common PAN applications like MP3 playing, e-mail viewing and photo sharing by 92% and extends the battery lifetime of mobile devices by up to 47% compared to current PAN management strategies.

1 Introduction

As the number of mobile computing devices owned by the average user grows, fast, energy-efficient mechanisms are needed to share data between those devices. Increasingly, photos, music, video, and text files are stored on both traditional computing devices such as laptops and handhelds, as well as consumer-electronic devices such as MP3 players, digital cameras, and personal video players. Although many recent models of such devices have built-in Bluetooth or WiFi (802.11b) wireless interfaces, transferring data between devices remains a tedious process that requires explicit user involvement.

Personal-area networks (PANs) are a promising technology for sharing data with minimal user distraction. When devices come within wireless radio range of each other, they can self-organize to form a PAN and share data. The resultant PAN can present the user with a common, distributed namespace for all of the user's personal data located on its members. For example, an MP3 player with PAN support could offer to play not just the songs located on its local storage, but also the songs stored on a nearby laptop or portable media player owned by the same user.

Unfortunately, these advantages come at a price: personal-area networks can substantially reduce the battery lifetime of mobile devices. Wireless interfaces typically consume a significant portion of the battery energy of a small computer. For instance, our results show that maintaining a single Bluetooth connection decreases the battery lifetime of an iPAQ 3970 handheld computer by over 14% and that keeping a WiFi interface active shortens battery lifetime by 53%. Thus, energy considerations often prohibit maintaining continual PAN connections for sharing data among co-located mobile devices.

The solution to this dilemma is to scale the network to meet the demands of applications. When applications are actively sharing data, the PAN should operate in a high-power mode that allows high-bandwidth, low-latency communication. As PAN usage decreases, the PAN should automatically enter modes that require less power to operate (but offer less efficient communication). During idle periods when the network is unused, the PAN should expend only the minimal amount of energy required to maintain connectivity.

In this paper, we present PAN-on-Demand, a system that allows mobile devices to self-organize into a personal-area network and share data without explicit user involvement. PAN-on-Demand adopts a centralized approach to organization and communication that reduces the energy demands for poorly-provisioned devices within the network. It uses distributed self-tuning power management (DSTPM) algorithms to adapt its operating behavior to match the needs of applications. PAN-on-Demand switches between different radio technologies and employs power-saving strategies to offer high-bandwidth, low-latency communication when network usage is high, while requiring only minimal energy to operate when network usage is low.

PAN-on-Demand also reorganizes the network structure to match the communication patterns of its members. If a device is actively communicating, it is migrated to the hub of the network. This improves performance and extends battery life by shortening the routes for its data transfers. Reorganization also allows PAN members that are not actively communicating to save power by turning off network interfaces and using power-saving strategies. Our results show that the adaptive strategies of PAN-on-Demand extend the battery lifetime of mobile devices by up to 47% for MP3, e-mail and photo sharing traffic compared to the static PAN communication strategies that require PAN members to keep their interfaces continuously active.

2 PAN background and assumptions

A personal-area network connects mobile computers and consumer electronics devices owned by the same user through short-range wireless radios. Since PAN members are usually co-located, we assume in our work that all PAN members are within wireless range of each other; thus, any two members can communicate directly if they have the same type of wireless interface. We have validated that this assumption holds using our experimental testbed, which places PAN members up to 20 feet apart.

Current mobile computers often have multiple wireless interfaces. For instance, laptops and handhelds typically ship with both WiFi and Bluetooth. Newer models of consumer-electronic devices such as cameras and cell phones are increasingly being shipped with wireless radios. While multiple interfaces are less common in consumer electronics, some devices such as the Motorola E680 cell phone [14] can currently support both Bluetooth and WiFi. PAN-on-Demand uses the presence of multiple interfaces to adapt network behavior to meet application demand. For instance, Bluetooth provides lower throughput than WiFi and increases network latency; yet, its power consumption is typically much less. The difference in characteristics between the two interfaces allows PAN-on-Demand substantial opportunity for optimization. PAN-on-Demand also takes advantage of power-saving strategies for each interface. For example, the power required by a Bluetooth interface can be reduced by dropping active connections and re-establishing them when needed.

PAN-on-Demand allows any member of the PAN to be either the initiator or recipient of network communication. This policy requires that each member keep at least one network interface active at all times so that it can receive incoming traffic. To save energy, a PAN member may turn off all of its interfaces except the one that uses the least power. For the remaining interface, a member may employ power-saving strategies such as dropping active connections. Ideally, during idle periods when a member is not actively communicating, it should expend only the minimal energy needed to allow it to be signaled when another PAN member wishes to communicate.

PAN-on-Demand currently assumes that all members have at least a Bluetooth interface. It uses Bluetooth for signaling, control traffic, and device discovery. Our implementation uses Linux's BlueZ Bluetooth protocol stack, which does not support the formation of scatternets [3]. Scatternets allow a single device to be a master and a slave simultaneously. Without scatternet support, a single device can have only one role at any given time. However, one master may have many slaves, and thus may have many simultaneous connections. We felt that the benefit of using a relatively well-supported protocol stack outweighed the potential lack of support for advanced features.

While PAN-on-Demand techniques are general and can support other network technologies, our current implementation is deployed on commodity hardware that supports only Bluetooth and WiFi. We have characterized the performance and energy cost of these two interfaces using our testbed — Section 7 gives these results. To use additional network technologies, a similar characterization would need to be done for each new technology. It would also be necessary to enumerate and characterize the possible power-saving strategies for each technology. We envision that this characterization could potentially be done by the manufacturer of each wireless network interface and specified by the network device driver.

3 Design principles

We next describe the three principles we followed while designing PAN-on-Demand.

3.1 Some peers are more equal than others

Our first design principle is that each member should contribute to the PAN in proportion to its abilities. At first glance, an architecture in which PAN members act as peers, with equal roles and duties, seems promising. However, mobile computers currently exhibit a wide disparity in provisioning. Some mobile devices, such as laptops, have large battery capacity, ample storage, and substantial processing power. Other devices, such as MP3 players and cell phones, are poorly provisioned, often having smaller batteries and less storage capacity. An architecture that treats all mobile computers equally can exhaust the resources of the poorly-provisioned devices while barely taxing the resources of well-provisioned devices.

For example, maintaining PAN membership requires a constant power expenditure. If all devices contribute an equal amount of power, a handheld computer with a small battery would quickly run out of power after joining a PAN. At the same time, a laptop with several more orders of magnitude of energy in its battery would be relatively unaffected by the power drain of PAN membership.

PAN-on-Demand adopts a centralized network architecture that asks more from well-provisioned devices while demanding less from poorly-provisioned ones. At any given time, a single device acts as the network *manager*, while the other devices in the network act as *workers*. When possible, power-intensive tasks are shifted to the manager to minimize the power drain of PAN membership for workers.

The manager coordinates PAN membership — it accepts new devices into the network and detects when devices leave. The manager also acts as a central hub for communication. Control traffic (e.g., the initiation of new data transfers) always is routed through the manager. This strategy allows the manager to monitor the traffic load of all applications within the network and trigger a reorganization of the network topology if necessary. For instance, if only two workers are actively communicating, performance is improved by making one worker the manager.

In contrast, data transfers may either traverse a direct link between the two endpoints or they may be routed via the manager using a two-hop route. The decision of which route to use is made dynamically, taking into account the network interfaces available on the communicating PAN members and their current power states.

3.2 Scale the network with demand

Our second design principle is that the characteristics of a PAN should match the immediate needs of its applications. Since current wireless technologies offer a trade-off between power and performance, selecting the correct interface can substantially affect system behavior. When an interactive application is actively using the PAN, a network that delivers crisp performance to the user seems best. When the network is idle, a low-power option that extends the battery lifetime of member devices is preferable. Clearly, no static choice for network communication can be best in both of the above scenarios. Therefore, PAN-on-demand adopts an *adaptive* strategy that dynamically chooses a network interface and power management strategy that matches the activity of the applications using the network.

In PAN-on-Demand, each worker independently chooses which network interface it will employ for communication and which power saving mode it will use for that interface — each worker makes this choice based on the network traffic that it expects to see in the near future. The manager allows this flexibility by supporting multiple communication modes. For instance, a PAN-on-Demand manager can receive and send data on its WiFi interface from workers that currently prefer high-quality communication, while simultaneously receiving and sending data on its Bluetooth interface from other workers that desire low-power communication.

Workers use both reactive and proactive self-tuning power management (STPM) strategies to decide which communication mode they will employ. PAN-on-Demand applications disclose their network activity, and the PAN layer adapts the network interface and power-saving mode to match the activity. If an application discloses that a large network transfer is about to occur and the PAN layer calculates that a higher-quality communication mode will save energy and/or provide better performance, the worker *reactively* switches to the higher-quality mode before the transfer begins. If a worker sees many network transfers in short succession, it may anticipate that many more transfers will occur in the near future — it then *proactively* switches to a higher-quality mode to better service the expected future activity. Similarly, when a worker sees an idle period with little network activity, it proactively switches to lower-power communication modes to preserve battery energy. Section 6 describes how these decisions are made.

3.3 Minimize user distraction

Our final design principle is to minimize the amount of supervision required from the user. The user's attention is a scarce resource in any computing system. This is especially true in a mobile environment in which users may be walking, driving, or performing other critical activities while using their computers.

PAN-on-Demand is designed to minimally distract its user. For example, a PAN member could potentially conserve battery energy by turning off all its network interfaces. However, before another device can initiate communication, the user would have to explicitly turn an interface back on. In effect, this would mirror the manual synchronization process currently used by many camera and MP3 players today, since the user would need to initiate the transfer at both communication endpoints. This process would be even worse for applications such as search that potentially involve many devices. For instance, if the user wished to locate a particular MP3 file within the PAN, the user would need to turn on all devices that could potentially store the file.

In contrast, PAN-on-Demand allows mobile computers to self-organize without user intervention. Computers owned by the same user that are within wireless radio range detect each others' presence and automatically form a PAN with one computer being the master and the others acting as workers. The resultant PAN requires some additional energy to maintain connectivity, but requires no explicit user interaction to transfer or search for data. The advantage of this design is that the user is not distracted by the need to explicitly enable communication on any single device since PAN-on-Demand keeps at least one interface on each member active to receive communication requests.

4 Cost metric

Before describing the implementation of PAN-on-Demand, it is useful to discuss how our system arbitrates between the competing goals of performance and energy conservation. In this section, we describe PAN-on-Demand's cost metric, which it uses to evaluate different options for network topology and communication strategies.

In accordance with the design principles outlined in the previous section, the cost metric balances the considerations of maximizing performance and battery lifetime while minimizing user distraction. The cost metric measures performance impact as the amount of time the user must wait for data to be transferred. This includes both the time to activate network interfaces, as well as the time to transfer the data over the PAN. Background transfers have no impact on performance (since the user is not waiting for them to complete).

Our cost metric also considers how much an activity would reduce the battery lifetime of the computers participating in the PAN. For each computer, we divide the amount of energy that the activity is predicted to consume by the average power usage of the machine when it is idle. The result is the estimated decrease in the computer's battery lifetime as a result of performing the activity. The cost metric sums this value for all participants in the PAN. If a PAN participant is connected to wall-power, activities have no impact on its battery lifetime.

In the sensor and ad-hoc networking communities, cost metrics often maximize the lifetime of the entire network [6, 21] — this is appropriate when the primary objective of the network is to perform a collaborative activity. However, in a PAN, the primary function of mobile computers is not to participate in the network — instead, it is to play music, take pictures, display e-mail, etc. Thus, it is appropriate to subordinate the needs of the network as a whole in preference to the needs of individual devices. Our cost metric captures this behavior by minimizing the impact of network participation on each computer.

To equate the relative impact of performance and battery lifetime, we turn to the user. PAN-on-Demand presents the user with a single knob, ranging in value from 0 to 1, that can be tuned to bias decisions toward performance or energy conservation. The simplicity of this interface is driven by our design principle of minimizing user distraction. More complex interfaces are certainly possible; e.g., separate knobs for each PAN participant or relative priority weighting for different computers — however, we chose an interface that would give the user the most control with the least effort.

In summary, PAN-on-Demand uses the following metric:

$$C = kT + (1-k)\sum_{j=1}^{members} E(j)/P_{base}(j) \qquad (1)$$

where C is the calculated cost, k is the global knob that is adjusted by the user, T is the time the user waits for the activity to complete, $E(j)$ is the amount of energy used by PAN member j to perform the activity, and $P_{base}(j)$ is the *base power*, the amount of power consumed by member j when it is turned on but running no additional activities.

5 Self-organization

PAN-on-demand provides an automated, energy-efficient mechanism that enables co-located personal devices to self-organize into a personal-area network. Self-organization consists of three phases: discovery, network entry, and reorganization. During the discovery phase, devices detect the presence of other devices owned by the same user that are co-located within wireless radio range. Once devices discover each other, the network entry phase begins, during which the devices form a PAN with one device serving as the PAN manager and the rest as workers. The choice of manager in this phase is driven by static characteristics of each device such as their base power usage and known wireless interfaces. After the network is formed, the network enters the reorganization phase, during which the PAN manager monitors the traffic patterns of the applications using the network. Based upon recent traffic, the manager may determine that the cost metric detailed in the previous section is likely to be minimized if a different member serves as manager. In this case, the current manager delegates its role to that member.

The next three subsections describe these three phases in more detail. Section 5.4 describes how members leave the PAN.

5.1 Discovery

Isolated devices and PAN managers periodically initiate the discovery phase of self-organization by performing a Bluetooth inquiry to locate nearby devices owned by the same user. PAN workers do not need to perform periodic inquiries since their network manager performs this activity on their behalf. This is one benefit of centralizing functionality at the manager: only the manager expends battery energy to perform common activities.

All Bluetooth-enabled devices within radio range respond to an inquiry if they do not have an active connection in which they are acting as a slave device. The inquiry response contains the Bluetooth device address of the responder — this address is sufficient to uniquely identify each device. All isolated devices and PAN managers respond to an inquiry. Since PAN-on-Demand does not require workers to maintain an active connection to their managers, a worker device may respond to an inquiry if it does not have an active Bluetooth connection.

Each device stores a *device list* that contains all personal devices owned by its user. The device list is sorted by capabilities, with well-provisioned devices that are most likely to serve as managers at the top of the list and poorly-provisioned devices at the bottom. The device list allows each device to identify which set of devices within its radio range belong to the same user. If a response is received that includes an identifier not on the device list, then the responding device is assumed to belong to a different user and is subsequently ignored.

The device list is sorted so that the devices with greater base power precede devices with lower base power. Devices with the highest base power tend to minimize the cost metric when they serve as manager, since the constant power expenditure of being the manager has the least relative impact on their battery lifetime. For instance, if serving as manager consumes an extra 0.5 Watts of power, the battery lifetime of a handheld with base power usage of 1 Watt will be reduced by 33% if it is the manager. Alternatively, a laptop with base power usage of 30 Watts will see its battery lifetime reduced by only 1.7% if it is the manager.

The device list provides a good hint about which device is most likely to serve as the PAN manager. If a device receives inquiry responses from one or more devices ranked higher than itself on the device list, it initiates the network entry phase of the protocol, during which it attempts to join a PAN with the highest-ranking device that it discovered serving as the master. However, if all inquiry responses that a device receives are from devices that rank lower on the device list, then it does not initiate the network entry phase of the protocol. In this case, the device expects that it will serve as master in the eventual PAN that will be formed. It waits for the other devices to initiate their own discovery phases, discover its presence, and establish connections as slaves. This policy reduces the need for subsequent reorganization since the device that is most likely to be chosen as the manager of the PAN once it stabilizes becomes the manager during the initial PAN formation.

We currently assume that the device list is statically configured on each device owned by a common user. We plan to eventually allow devices to exchange updates to the device list during PAN formation. This will allow a user to make a change such as adding a new device in only one location. PAN-on-Demand will epidemically propagate the change to all other devices that they own.

5.2 Network entry

During the network entry phase, an *initiating device* attempts to form a PAN with a *discovered device*. The discovered device is the highest-ranking device on the device list that responded to the initiating device. The initiating device may be either an isolated device or the manager of an existing PAN with one or more workers. We first describe the network entry phase for the case where the initiating device is an isolated device, and then extend the protocol to deal with PAN managers.

If the initiating device is an isolated device, it connects to the discovered device as a Bluetooth slave. The discovered device may itself be an isolated device — in this case, the discovered device accepts the connection, sends back an acknowledgment, and acts as a manager for the newly formed PAN. If the discovered device is already the manager of an existing PAN, it accepts the connection, sends back an acknowledgment, and adds the initiating device as another worker in its PAN.

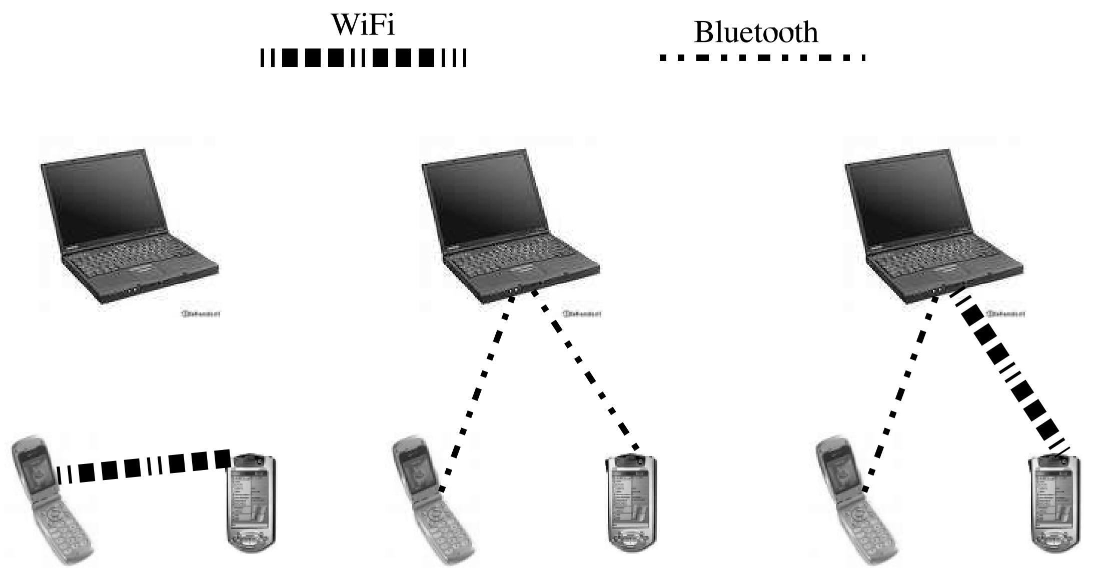
Infrequently, the discovered device may be a worker in an existing PAN. This case occurs when the Bluetooth connection between the worker and its manager has been previously dropped to save power. In this case, the discovered device sends back a negative acknowledgment that includes the Bluetooth device address of its manager. The initiating device then connects to the discovered device's manager. If the initiating device is unable to establish a connection at any point during this process, the network entry phase ends. If that happens, the initiating device must re-run the discovery protocol before it joins a PAN.

If the initiating device is a PAN manager with one or more workers, it waits for existing communication within its PAN to quiesce. Once no data transfers are in progress, it sends a message to its workers informing them of the Bluetooth device address of the discovered device. It terminates its existing Bluetooth connections and attempts to connect to the discovered device using the protocol described above for isolated devices. Its workers also attempt to connect to the discovered device using the same protocol.

5.3 Reorganization

Once a PAN has been formed by the completion of the network entry phase, the network enters the reorganization phase. During this phase, the manager monitors PAN traffic to analyze communication patterns. If it was not the ideal manager for recent communication (e.g., the cost metric would have been lower if some other member has served as manager), then the current manager triggers a network reorganization during which the more optimal member assumes the role of manager. The reorganization process is based on the assumption that future traffic will resemble the traffic seen on the network in the recent past. Of course, this assumption could be wrong. In that case, it is likely that another node will be selected as manager in the future, triggering a subsequent PAN reorganization.

To determine when reorganization is necessary, the PAN manager logs the size of each transfer and the state of all network devices along the possible routes for that transfer. This is another benefit of centralization — since



(a) WiFi-only (b) Bluetooth-only (c) Hybrid

This shows three possible strategies for transmitting data between two workers using WiFi and Bluetooth interfaces. (a) is a direct point-to-point transfer using WiFi. (b) is a two-hop Bluetooth route through the manager. (c) is a hybrid route through the manager that uses both WiFi and Bluetooth.

Figure 1. Three modes for transferring data in a PAN

the manager sees all communication requests and responses, no further communication is required to get information for the log. The transfer data are written to a circular buffer that holds a maximum of 50 entries — after the buffer fills, the oldest record is evicted when space is needed. For each PAN member, the current manager calculates the amount of time the transfer would take if that member had been the manager of the network at the time the transfer began. It also calculates the amount of energy that would be expended by each participating member. It uses the metric in Equation 1 to determine the cost that would have been incurred for that transfer based on the calculated time and energy values. Based on these cost values, the manager calculates the total cost over the period covered by the transfer log, assuming that a particular device had been the PAN manager:

$$C_{total}(M) = \sum_{i=1}^{transfers} C_i(M) + (1-k)\frac{P_{manager}(t_n - t_1)}{P_{base}(M)} \tag{2}$$

C_i is the calculated cost of the i'th transfer if M had been the manager. $P_{manager}$ is the constant power drain that a member incurs by serving as the manager. $t_n - t_1$ is the time between the first and last transfers recorded in the log.

If the manager determines that C_{total} is smaller for one of its workers than it is for the manager and if the difference between the two values is greater than a threshold value, it triggers a reorganization. We set the threshold value to be the cost of the reorganization itself. This is the additional energy expended by all other workers to disconnect and reconnect their Bluetooth interfaces, as well as the energy required to transfer the manager role between the two devices.

The manager waits for all current data transfers to end. It sends a message to all of its workers informing them of the reorganization and the Bluetooth device address of the new manager. It then disconnects from its workers and reconnects to the new manager as a Bluetooth slave. All other devices within the PAN also reconnect to the newly chosen master.

5.4 Leaving the PAN

Network partitions and device disconnections are discovered passively, when a communication request fails to complete. When a PAN manager fails to contact a worker to satisfy a request, it assumes that the worker has left the PAN. The manager removes the worker from its list of PAN members. When a worker fails to contact its manager, it becomes an isolated device. It periodically initiates device discovery and attempts to form a new PAN when it next locates a nearby device owned by the same user.

6 Distributed STPM

PAN-on-Demand uses distributed self-tuning power management (DSTPM) to set the power states of the network interfaces on each member. The algorithms we use are based on the self-tuning power management algorithms [1, 2] that we previously developed to manage a single storage and/or network device on a single computer. In this paper, we extend these algorithms to a distributed environment in which we manage multiple network interfaces on multiple computers.

Extending self-tuning power management to the PAN environment presented several challenges. First, we defined an appropriate cost metric that expressed performance and energy conservation goals for all the members of a network, not just a single computer. This metric has already been described in Section 4. Next, as discussed in Section 6.1, we defined the possible strategies for transmitting data within the PAN and developed a reactive strategy for dynamically choosing the best transmission strategy and network route. Finally, we developed proactive strategies that switch between multiple interfaces and manage control connections. These strategies are discussed in Sections 6.2 and 6.3.

6.1 Choosing the best transfer strategy

When a PAN-on-Demand member initiates a new data transfer, it uses DSTPM to choose the best communication strategy. This is a purely reactive decision that minimizes the cost of the transfer given the expected size of the transfer, the performance and energy characteristics of the available network interfaces, and the present state of the network. The questions to be answered are:

- What route should be used to transfer the data?
- What wireless technology should be used for each hop along that route?

The initiator first sends a communication request to the target device via the PAN manager. This message contains the expected size of the transfer (if known to the initiator), the type and power state of the initiator's network interfaces, and the initiator's base power. The manager appends the state of its network interfaces and its base power to the message.

After the target device receives the communication request, it has all the information it needs to evaluate the cost metric described in Section 4. The target device first computes the expected time and energy to perform the transfer for each possible communication strategy. Such a calculation is straightforward given the size of the data to be transfered and a characterization of the network interface such as the ones provided for Bluetooth and WiFi in Section 7.

If either the initiating or target device is the PAN manager, only a one-hop route is considered. In this case, the decision is whether to employ Bluetooth or WiFi for the transmission. If both devices are workers, then the three strategies shown in Figure 1 are possible. The data may be transferred using a Bluetooth connection, in which case a two-hop route is needed since the BlueZ stack does not support worker to worker communication. The data may also be transferred using a one-hop WiFi connection. Alternatively, data may be routed through the manager with one hop using Bluetooth and the other WiFi. A hybrid Bluetooth/WiFi strategy is most useful when one worker has disabled its WiFi interface at the start of the transfer while the other has an active interface. The hybrid strategy can also be used when one member does not have a WiFi interface. While it is feasible to transfer data using a two-hop WiFi route through the manager, PAN-on-Demand always chooses the one-hop route since it offers better performance and energy conservation.

The target device calculates the value of the cost metric for all feasible transfer strategies. It chooses the strategy with the smallest cost and communicates its decision back to the initiator via the manager. The target device appends the state of its interfaces to its response so that the manager can log the information and use it to determine when reorganization is needed. Both the manager and initiator examine the reply to determine if they need to enable a network interface for the upcoming data transfer.

6.2 Proactive energy savings

DSTPM reduces the energy cost of PAN membership by turning off network interfaces and employing power-saving strategies when applications are not using the PAN. Currently, a PAN worker can be in one of four states:

- **WiFi**. Both the Bluetooth and WiFi interfaces are active, and a Bluetooth connection exists with the manager. This state uses the most power, but also offers the best performance since no mode transition is required to send either control or data traffic.
- **BT-connected**. The worker's WiFi interface is disabled, its Bluetooth interface is active, and an active connection exists with the manager. This state uses less power than the WiFi state, but offers poorer performance for data transfers since data must either be transferred via Bluetooth or the transfer must wait for the WiFi interface to be turned on.

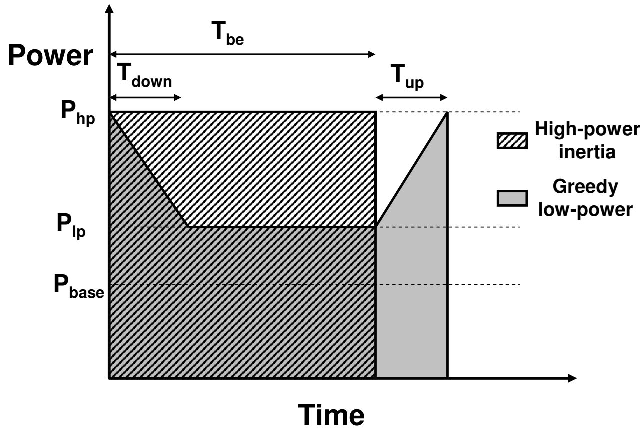


Figure 2. Break-even illustration

- **BT-sniff**. The WiFi interface is disabled. The Bluetooth connection is placed in a power saving *sniff* mode. In this mode, connected devices initiate network communication with one another only at pre-determined periods, allowing them to turn-off their radios at other times. Sniff mode adds latency to the Bluetooth communications but allows better energy conservation for the members.
- **BT-unconnected**. The WiFi interface is disabled. The Bluetooth interface is active but no connection exists between the worker and the manager. This state uses the least energy but offers the poorest performance. Before a new transfer begins, an expensive Bluetooth connection must be re-established with the manager to send the communication request.

PAN members can enter a higher-power state either as the result of a data transfer (as described in the previous section) or due to a proactive transition (as described in the next section). If the time and energy cost of transitioning between power modes were negligible, then each member would simply enter the minimum-power mode when it is not participating in data transfers. However, our results show that it often takes several seconds to enable network interfaces and transition between power modes. Since data transfers are often closely correlated in time, a new transfer is more likely to occur if transfers have occurred in the recent past. In such circumstances, a proactive strategy that keeps interfaces in high-power states for a short time after a transfer ends has been shown to work best [2, 11].

DSTPM uses a break-even timeout strategy [8] to decide when to transition from a higher-power state to a lower-power state. This strategy compares two policies: a *high-power inertia* policy that continues to employ the current high-power state, and a *greedy low-power* policy that immediately switches to a low-power state. The break-even time, T_{be}, is the inter-arrival time for data transfers for which these two strategies yield equivalent results. If the next transfer starts before the break-even time, the high-power strategy is superior; otherwise the low-power strategy is best.

Figure 2 illustrates how DSTPM calculates the break-even time. The y-axis on this graph is power usage, and the x-axis is time. The energy expended by each strategy is the area under its curve. Thus, the energy used by the high-power inertia strategy is given by the area of the striped region: specifically, it is product of P_{hp} (the power used in the high-power mode) and T_{be} (the time until the next activity begins). The cost of the high-power inertia strategy is:

$$C_{hpi} = (1-k)\frac{P_{hp} * T_{be}}{P_{base}} \quad (3)$$

Since the high-power strategy does not add any delay, its cost is measured solely in the energy cost of keeping the member in the high power mode.

In contrast, the cost of the greedy low power strategy consists of both the energy used by the PAN member and the time the user must wait for the transition back to the high-power mode before the next transfer begins (T_{up}). The shaded area of Figure 2 shows the energy used by the greedy low-power strategy — this consists of the sum of the energy used in three distinct regions. The energy used in the first region, E_{down}, is the energy used by the device to transition from the high-power to the low-power mode. The second region is the period the device operates in the low-power mode — the energy of this region is the product of P_{lp} (the power used in the low-power mode) and $T_{be} - T_{down}$. The final region is the transition to the high-power mode before the next activity begins — the energy used in this region is given by E_{up}. According to the cost metric of Equation 1, the cost of the greedy low-power strategy is:

$$\begin{aligned} D_M &= \frac{E_{up} + E_{down} - P_{lp} * T_{down}}{P_{base}} \\ C_{glp} &= k * T_{up} + (1-k) * [\frac{P_{lp} * T_{be}}{P_{base}} + D_M] \end{aligned} \quad (4)$$

One can think of D_M as the extra energy expended by the greedy low-power strategy beyond the energy required to keep the device in the low-power mode for the break-even time.

The value of T_{be} is calculated by equating C_{glp} and C_{hpi}. Solving for T_{be} yields:

$$
\begin{aligned}
s_M &= \frac{P_{hp} - P_{lp}}{P_{base}} \\
T_{be} &= \frac{k * T_{up} + (1-k) * (D_M)}{(1-k) * (s_M)}
\end{aligned}
\tag{5}
$$

s_M is the surplus rate of battery consumption by the high-power mode compared to the low-power mode.

The above calculation of T_{be} can be applied to any transition that affects only a single machine. For instance, in our current implementation, it applies to the transition from the WiFi mode to the BT-connected mode. In contrast, the transition from the BT-connected mode to the BT-unconnected mode affects both the worker and manager since the Bluetooth connection is dropped at both ends. The decision must therefore account for the energy used by both devices. The calculation of the break-even time for this transition is:

$$
T_{be} = \frac{k * T_{up} + (1-k) * (D_{wkr} + D_{mgr})}{(1-k) * (s_{wkr} + s_{mgr})} \tag{6}
$$

Each worker uses DSTPM to independently change the power states of its interfaces. Thus, a worker that is actively participating in data transfers may be in its high-power mode, while another worker that has been idle for a substantial time may be in its lowest-power mode. The manager independently decides to turn off its WiFi interface. However, the manager defers the decision of when to drop Bluetooth connections to its workers.

6.3 Proactive performance improvement

In order to transfer data, a PAN worker must leave the BT-unconnected state since a Bluetooth connection is required to send or receive control messages from the manager. However, a worker need not ever enter the WiFi state to transfer data. If each transfer is small, the transition cost of turning on its WiFi interface will be greater than the potential performance and energy benefit of performing the transfer using WiFi instead of Bluetooth. In this case, the reactive strategy described in Section 6.1 will always use Bluetooth to transfer the data.

However, if a member were to perform several short transfers in short succession, the cost of the transition could be amortized over many transfers and lead to an overall reduction in the cost metric. To deal with such instances, a proactive strategy is needed to transition to the WiFi state when many short transfers are likely to occur in the near future.

When a worker performs a transfer in Bluetooth, it calculates the time and energy reduction (if any) that it would have seen had its WiFi interface been active at the start of the transfer. Using the cost metric of Section 4, it calculates the opportunity cost of being in the BT-connected state. It adds the opportunity cost (if any) to a running total of such costs every time it performs a Bluetooth transfer. From this total, it subtracts the cost of the additional energy that would have been expended keeping the WiFi interface active during the idle periods between transfers. The running total is not allowed to go below zero.

When the accumulated opportunity cost exceeds a threshold, the PAN member turns on its WiFi interface. This decision reflects the assumption that it is likely to see several more short transfers if it has seen several in the recent past. PAN-on-Demand chooses the threshold value based upon the break-even calculation in the previous section. Since the member will remain in the WiFi mode for T_{be} if it sees no more data transfers, the cost of the incorrect transition, C_{thresh}, is:

$$
C_{thresh} = (1-k) * [T_{be} * s_M + D_M - \frac{P_{lp} * T_{up}}{P_{base}}] \tag{7}
$$

7 Characterizing PAN usage costs

The DSTPM algorithms in the previous section are general. They do not assume particular performance and energy usage values for any network interface. Thus, before using them, it is necessary to first characterize the network interfaces that will be employed. In this section, we report on our characterization of two interfaces (Bluetooth and WiFi).

7.1 Methodology

We have deployed PAN-on-Demand on an experimental testbed consisting of several HP iPAQ 3970 handheld computers. All iPAQs run the Linux 2.4.18-rmk3 kernel and have a 206 MHz StrongArm processor, 64 MB of DRAM, and 32 MB of flash memory. Each iPAQ has two wireless interfaces: a built-in Bluetooth interface and a Cisco 350 802.11 PCMCIA card.

The iPAQs are deployed approximately 10–20 feet apart in an office environment. The transmit power of the Cisco cards is set to 1 mW. We found this value to be sufficient to transmit the distances required of our testbed, despite the presence of several nearby WiFi access points.

We measured performance using the `gettimeofday` system call. We measured energy used by the iPAQs

Interface State	Idle Power (Watts)	Latency (seconds)	Throughput (Kbps)	Transmit Power (Watts)	Receive Power (Watts)
$BT_{connected}$	0.24 (0.00)	0.032 (0.003)	520 (4)	0.69 (0.01)	0.49 (0.00)
WiFi	1.44 (0.00)	0.002 (0.000)	4429 (64)	1.72 (0.01)	1.86 (0.02)

This figure shows the time and energy characteristics of Bluetooth and WiFi interfaces on an iPAQ 3970 handheld. Each value shows the mean of five measurements with standard deviation given in parentheses.

Figure 3. Performance and energy characteristics of wireless interfaces

with an Agilent 34401A digital multimeter. We removed the batteries from each iPAQ and sampled current drawn through the iPAQ's external power supply approximately 50 times per second. We calculated system power usage by multiplying each current sample by the mean voltage drawn by the iPAQ — separate voltage samples are not necessary since the variation in voltage drawn through the external power supply is very small. We calculated total energy usage by multiplying the average power drawn during benchmark execution by the time needed to complete execution.

7.2 Idle power usage

With no network interfaces active, an idle iPAQ uses 1335 mW of power. If the Bluetooth interface is active, the iPAQ uses an additional 125 mW. Since the Bluetooth interface must be kept continually active for PAN-on-Demand, this 125 mW represents the minimal cost of PAN participation. It is encouraging that the relative power consumption is less than 10% of the idle power of a small, mobile device such as the iPAQ. Potentially, the cost could be further reduced by using extremely low-power radios similar to those used by the Wake-on-Wireless [20] project. However, given that the increase in idle power is small and given that Bluetooth interfaces are widely available on commodity hardware today, Bluetooth seems the best choice for PAN-on-Demand at the present time.

The second column in Figure 3 shows the additional power consumed by Bluetooth and WiFi interfaces on the iPAQ. Maintaining a Bluetooth connection between manager and worker uses an additional 240 mW of power on the worker and 120 mW on the manager. For each further connection, the manager expends an additional 20 mW. The substantial power cost of maintaining connections motivates our decision to drop Bluetooth connections between workers and the manager during periods of inactivity. Thus, an idle iPAQ in PAN-on-Demand would expend only the 1460 mW of base power required to enable other devices to initiate communication.

Figure 3 also shows the power expended by the Cisco WiFi interface in its ad-hoc mode. Although the 802.11 specification allows for power-saving modes in ad-hoc operation, we could find no commercial hardware that supported this functionality. Were such a power-saving mode to become available, we would simply add a fifth power mode to those described in Section 6.

7.3 Cost of transferring data

We next measured the time and energy to transfer data between the master and a worker in each interface mode. The third column in Figure 3 shows network latency, as measured by the time to perform a one-byte ping between worker and master. The fourth column shows the average throughput achieved while transferring a 1 MB file using a reliable protocol: L2CAP sockets for Bluetooth and TCP/IP sockets for WiFi. The final two columns report the average power used by the worker when sending data to the manager and when receiving data from the manager.

7.4 Transition costs

We also measured the time and energy required to transition between the various modes of PAN operation. During the measurement, a worker in an initial mode of operation transitions to a different mode, then completes a one-byte exchange of data with the manager. The one-byte exchange is necessary because some interfaces report completion of a transition long before they are ready to begin network activity in the new mode.

The first two rows of Figure 4 shows the time and energy required to establish and tear down a Bluetooth connection. There is substantial variation in the time required to create a Bluetooth connection due to the Bluetooth frequency synchronization delay between two machines [9, 19]. Thus, we have observed the time to establish a connection vary from 1.2 seconds to as much as 10.3 seconds. However, the median connection time is only 1.4 seconds. Since connection establishment adds considerable latency to a data transfer, PAN-on-Demand maintains Bluetooth connections when it predicts that the network is likely to be used in the near future. The remaining rows of Figure 4 show the time and energy required to enable and disable the WiFi interface.

In order to reduce the connection establishment latencies, Bluetooth specification allows devices to employ a range of power saving modes. Similar to

Interface	Initial state	Final State	Time (seconds)	Energy (Joules)
Bluetooth	Unconnected	Connected	3.18 (2.69)	1.33 (1.19)
	Connected	Unconnected	3.24 (0.37)	1.13 (0.14)
WiFi (802.11b)	Off	On	3.04 (0.02)	3.99 (0.37)
	On	Off	2.06 (0.13)	2.93 (0.03)

This figure shows the transition costs of Bluetooth and WiFi interfaces in on iPAQ 3970 handheld. Each value shows the mean of five measurements with standard deviation given in parentheses.

Figure 4. Transition costs of wireless interfaces

CoolSpots [16], we found the sniff mode that allows the Bluetooth radio to sleep for a specified period to be the most applicable one. Sniff mode allows Bluetooth to achieve power consumption levels of lower than the unconnected state as it does not need to respond to page scan requests. In order to balance the trade-off between request latency and power consumption, we chose to adjust the sleep period so that the devices would consume only 1% more power than Bluetooth unconnected. This period was 400 ms for our experiments. Hence, the expected latency for sniff mode in our experiments is 200 ms. Our measurements showed that the transition to sniff mode can be achieved at a negligible cost (less than 10 ms and 10 mJ).

8 Evaluation

Our evaluation answers the following questions:

- How much time and energy is consumed by PAN self-organization and maintenance?
- How does the latency and battery lifetime using PAN-on-Demand compare to the other WPAN communication strategies?
- How much benefit is achieved by reorganizing the network structure?
- What is the impact of employing additional power saving modes for the radios?

We used the experimental testbed and methodology described in Section 7.1. When evaluating PAN-on-Demand, we used a value of 0.5 for the user-adjustable knob — this gives equal weighting to performance and battery lifetime in the cost metric.

8.1 Cost of self-organization

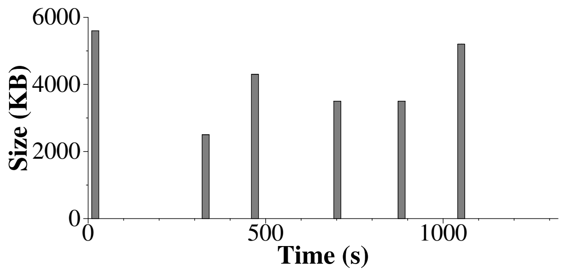
We began by measuring the time and energy required to perform a Bluetooth inquiry. In PAN-on-Demand, all managers and isolated devices perform a periodic inquiry to detect if other devices owned by the same user have come within radio range. Our measurements show that an inquiry takes 10.3 seconds and uses 4.3 Joules of energy. These results show that performing a periodic inquiry every five minutes (the current interval we use for PAN-on-Demand) will reduce the battery lifetime of an iPAQ by slightly less than 1%.

Next, we measured the time and energy needed for a new member to join the PAN. In this experiment, an isolated device comes into wireless range of an existing PAN with a manager and a single worker. The isolated device joins the PAN as an additional worker. Given an inquiry period of 5 minutes, the expected time for the isolated device to begin a new inquiry after coming within wireless range of the PAN is 150 seconds. By performing inquiries more frequently, this expected time could be reduced, but then inquiries would consume more than 1% of the battery lifetime of small devices like the iPAQ. Once the inquiry begins, the new device takes, on average, an additional 12.2 seconds to join the PAN. During this period, the isolated device consumes 22.7 Joules of energy and the PAN manager consumes 6.0 Joules — this includes the time and energy to perform the inquiry.

Finally, we measured the time and energy needed to reorganize the PAN. This experiment starts with a PAN consisting of three iPAQs in the BT-connected state. The existing PAN manager selects one of its workers to act as the new manager, signals the reorganization to its workers, and disconnects. The newly selected manager reestablishes Bluetooth connections to the other two nodes. Our measurements show that this process takes 7.5 seconds to complete, with the original manager joining the new PAN after 4.5 seconds, and the other worker joining 3 seconds later. The original manager consumes 3.6 Joules of energy during reorganization, while the newly selected manager consumes 3.8 Joules. Other PAN members consume 3.1 Joules during reorganization.

8.2 Impact of PAN-on-Demand

Next, we compared PAN-on-Demand to three current PAN communication strategies. The first comparison is a WiFi-only strategy where the members communicate directly with one another using only their WiFi radios. PAN members keep their WiFi interfaces continuously active, but disable their Bluetooth interfaces. The sec-



This workload emulates 20 minutes of user fetching MP3 files from a storage server in the PAN and playing them on another device. The y-axis shows the size of the requested files and x-axis shows the time at which each request was made.

Figure 5. MP3 workload profile

ond strategy, Bluetooth-only, consists of all members maintaining a continuous Bluetooth connection with the manager and utilizing that link to transfer data with one another. The third is a hierarchical multiple radio strategy, similar to Wake-on-Wireless [20, 22], that uses the Bluetooth to signal WiFi radios to switch-on. PAN members exchange their intent to share data on the Bluetooth channel and perform the data transfer on WiFi channel. Since, this strategy does not implement any proactive technique to stay awake, WiFi radios are immediately switched off after every data transfer.

Since PANs are an emerging technology, there do not yet exist traces of actual PAN usage. We therefore chose three applications (MP3 playing, e-mail viewing, and photo sharing) that we felt would be likely candidates for this emerging environment. We evaluated the impact of PAN communication strategies on these applications using the iPAQs from our testbed as two WPAN workers and a manager.

For our evaluation, we compared the PAN communication strategies across two user-observable properties. First, we measured the average response time for all requests in the application trace. Second, we determined the change in battery lifetime of each PAN member by measuring the energy expended by each PAN member during the execution of the application trace. In order to calculate the impact on battery lifetime, we assume that the device would continue operating at its base power after the trace execution.

8.2.1 MP3 workload

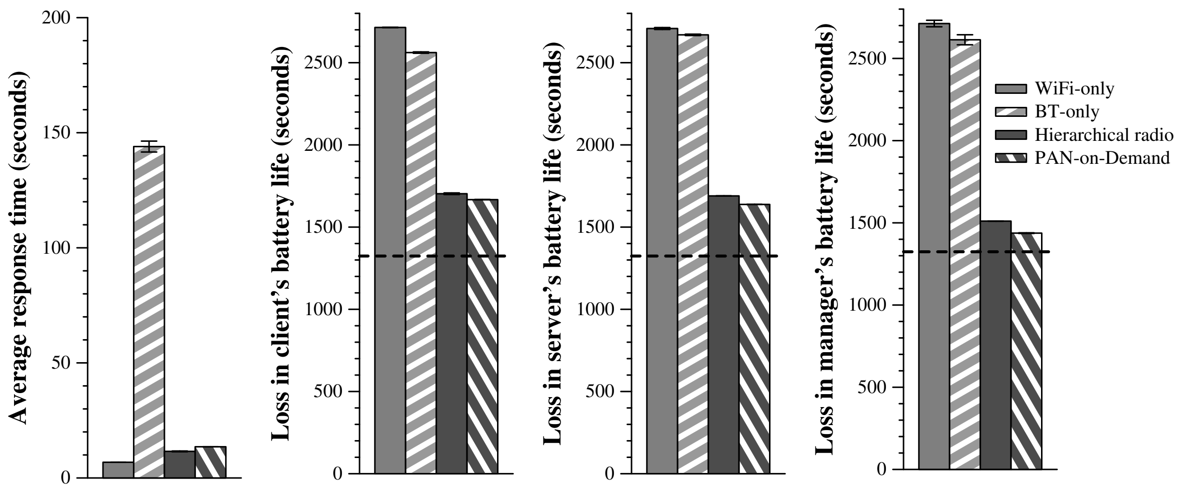
For MP3 playing, we consider a scenario in which all of a user's MP3 files are stored on a high-capacity mobile storage server such as Intel's Personal Server [23]. When the user selects a song from a mobile MP3 client, the file is fetched from the storage server via the PAN and played. When the song finishes, a new song is selected, fetched, and played on the MP3 client. Figure 5 shows the request profile of an MP3 workload that plays six songs ranging in duration from 139 to 331 seconds. The size of these files ranges from 2.5 to 5.6 MB. The total time to play all six songs is 1324 seconds — this is the minimal possible time to execute the trace.

Figures 6 show the average response time of all transfers in the run, as well as the impact on the battery lifetime of the client, server, and manager for the MP3 workload. Minimal possible time to execute the trace is also the minimal impact that the trace execution will have on the battery life of the members and is shown as dashed line in the figure. The WiFi-only strategy offers the best performance possible since it never disables an interface. However, it also reduces the lifetime of the mobile devices substantially compared to other strategies.

In comparison, PAN-on-Demand establishes a WiFi connection between the client and server to transfer all MP3 files. After each transfer finishes, it waits for the calculated break-even period (13.8 seconds) and then disables the WiFi interface. After an additional 52.4 seconds, PAN-on-Demand tears down the Bluetooth connections. These proactive strategies save considerable energy during the long network idle periods like when the songs are being being played. Compared to WiFi-only strategy, PAN-on-Demand extends the battery life of the PAN members by 39–47%. In this case, PAN-on-Demand adds an additional 7 seconds to the average response time of the requests due to the transition cost of establishing the Bluetooth connections and switching on the WiFi interfaces. As mentioned earlier, our evaluation considered that the user has equal preference for battery longevity and performance — when the user only cares about the performance, PAN-on-Demand tunes its behavior to match the WiFi-only strategy.

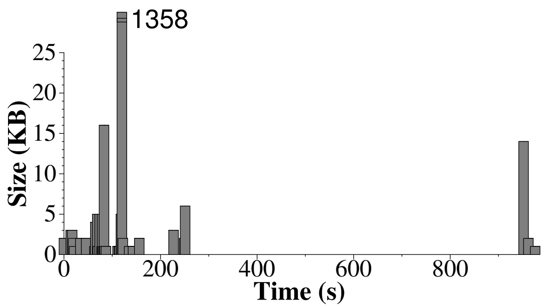
Surprisingly the Bluetooth-only strategy reduces the battery lifetime of the devices by almost as much as the WiFi-only strategy. Even though Bluetooth uses much less power than WiFi, its relative throughput is much smaller. Due to transmission delays, the trace takes much longer to finish. Since energy is the integral of power over time, the relative energy savings for the Bluetooth-only strategy are meager. In this case, PAN-on-Demand improves the average response time by an order of magnitude while extending the battery life by 35–45%.

The MP3 workload is an ideal scenario for the hierarchical radio strategy, since it consists of intermittent transfers of large data items. Clearly, the best strategy is to enable the WiFi radio on each data transfer request and immediately switch it off after the transfer completes. Compared to PAN-on-Demand, the hierarchical radio strategy provides 2 seconds faster response time at the expense of battery life (2–5%) as it does not tear down



This figure shows the average response time and the impact on the battery lifetime of the client, server and manager for a workload that emulates a user selecting and playing MP3 files. Dashed line represents the minimal impact that the trace execution will have on the battery life of the members which is equal to 1324 seconds for this workload. Each impact on the battery lifetime value shows the mean of three trials and each average response time value shows the mean of nine trials. The error bars are 90% confidence intervals.

Figure 6. Benefit of PAN-on-Demand for the MP3 workload



This workload emulates 20 minutes of user behavior of fetching e-mails from a storage device and reading them. The y-axis shows the size of the requested files and x-axis shows the time at which each request was made.

Figure 7. E-mail workload profile

the Bluetooth connections. Although the hierarchical radio strategy can improve the battery lifetime of PAN members by 10% by employing Bluetooth sniff mode, it would also add approximately 800 ms to the average response time for the requests.

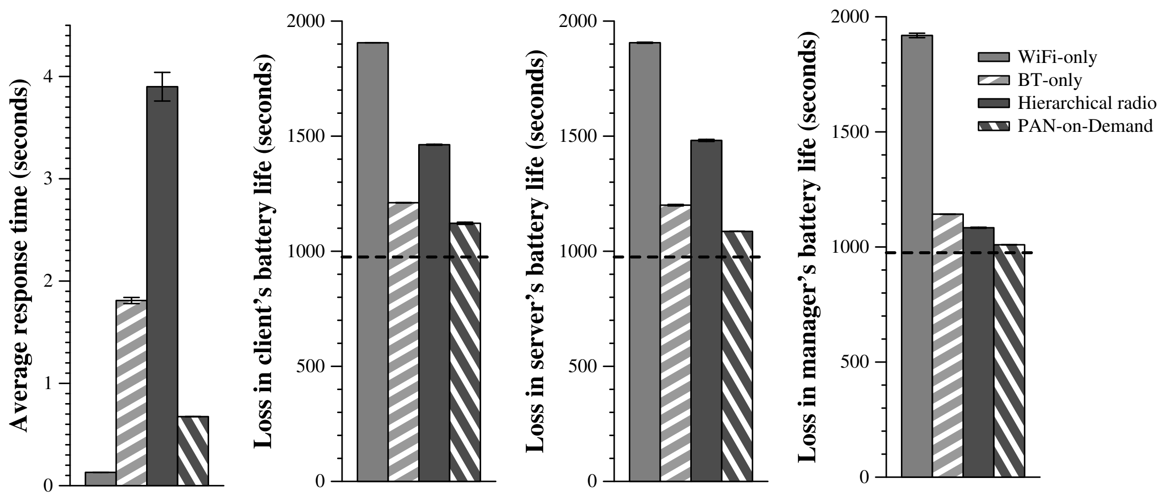
8.2.2 E-mail workload

For e-mail viewing, we consider a scenario where the e-mail has been previously downloaded from a server and is currently stored on a storage device within the PAN. When the user views each e-mail message on a PDA, the e-mail is fetched over the PAN from the storage device and displayed. Figure 7 shows the request profile of the workload of 975 seconds of e-mail client activity previously collected by our research group [2]. These e-mail messages vary in size from 1 KB to 1.35 MB.

Figure 8 shows the result of our execution. Proactive techniques for keeping the interfaces awake in PAN-on-Demand yield significant benefit for this workload. PAN-on-Demand adds only 590 ms to the average response time compared to the WiFi-only strategy since the typical request size is less than the reactive break-even size for WiFi transfer and the request inter-arrival time is less than the break-even time for tearing down the Bluetooth connections. Furthermore, the proactive network reorganization causes PAN-on-Demand to restructure the PAN on the 4th transfer request to improve both control and data message latency. Overall, PAN-on-Demand extends the battery life of the PAN members by 41–47%.

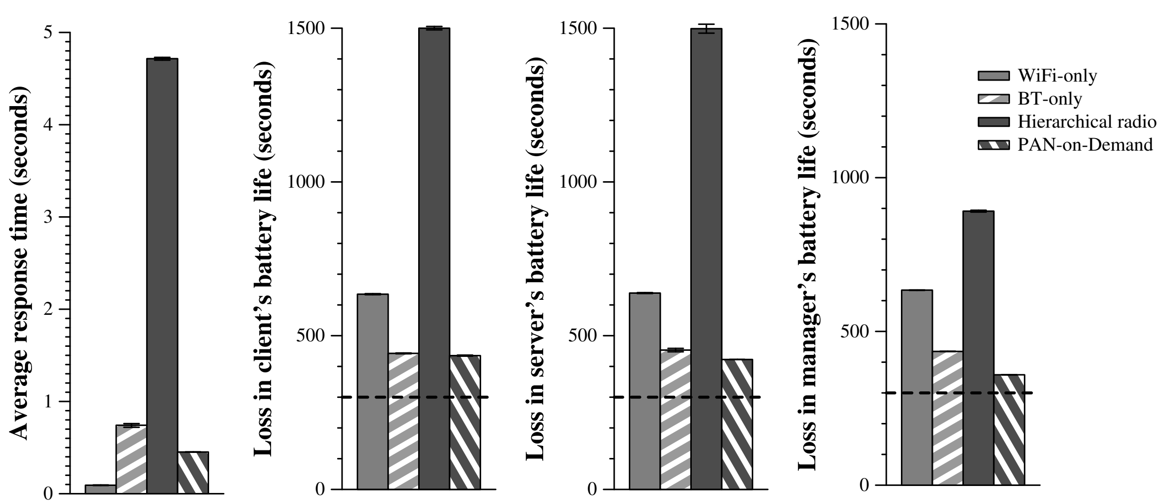
The small bursty transfers between members in this workload makes it a good workload for the Bluetooth-only strategy. However, the lack of network reorganization capability and the inability to adapt to the occasional large data transfers causes this strategy to perform poorly compared to PAN-on-Demand. This strategy ends up being 2.5 times slower and reduces the battery lifetime of the PAN members by 7–12% compared to PAN-on-Demand.

The nature of this workload is unpropitious for the hierarchical radio strategy. The hierarchical radio strategy has to pay the cost of transitioning the WiFi radios on each transfer and thus adds 3.9 seconds to the average response time. Compared to the hierarchical radio strategy, PAN-on-Demand provides 5.5 times faster response and extends the battery life of its members by 7–26%.



This figure shows the average response time and the impact on the battery lifetime of the client, server and manager for a workload that emulates a user fetching e-mails from a storage device and reading them. Dashed line represents the minimal impact that the trace execution will have on the battery life of the members which is equal to 975 seconds for this workload. Each impact on the battery lifetime value shows the mean of three trials and each average response time value shows the mean of nine trials. The error bars are 90% confidence intervals.

Figure 8. Benefit of PAN-on-Demand for the e-mail workload



This figure shows the average response time and the impact on the battery lifetime of the client, server and manager for a workload that emulates a user fetching photos from a storage device and viewing them. Dashed line represents the minimal impact that the trace execution will have on the battery life of the members which is equal to 300 seconds for this workload. Each impact on the battery lifetime value shows the mean of three trials and each average response time value shows the mean of nine trials. The error bars are 90% confidence intervals.

Figure 9. Benefit of PAN-on-Demand for the photo-sharing workload

8.2.3 Photo-sharing workload

For photo sharing, we created a trace to emulate a scenario where the user first views the thumbnails of 100 pictures stored on his digital camera and then views a full size image of 10 of those pictures on the PDA. Each thumbnail is 6 KB in size and each full size image is 100 KB. The workload consists of 300 seconds of user activity with 30 seconds of user think time between downloading two full size images.

Figure 9 shows the result of our execution. Similar to the results of e-mail workload, PAN-on-Demand adds 360 ms to the average response time and improves the battery life by 31–43% compared to the WiFi-only strategy. In this workload, the network reorganization takes place after the 2nd transfer and the proactive WiFi switch-up takes place after another 60 transfer requests.

The Bluetooth-only strategy does better in this case as the transfers are small, but it is still 1.5 times slower to respond than PAN-on-Demand. With respect to the impact on the client's battery lifetime, the Bluetooth-only strategy is slightly worse (1.5%) than PAN-on-Demand as the additional cost of network reorganization and WiFi switch-up compensate for the additional improvement that are obtained for the client. In contrast, the server and initial manager machines see an improvement of 7% and 17% respectively in the battery lifetime.

In this workload, the hierarchical radio strategy has to pay both the cost of switching up and switching down before each transfer request for a thumbnail. Thus, we see an average response time of 4.7 seconds (an order of magnitude slower than PAN-on-Demand) and a loss in battery lifetime by 60–72% compared to PAN-on-Demand.

8.3 Impact of reorganization

We studied the impact of network reorganization by comparing the execution of PAN-on-Demand with its implementation when reorganization is turned off. We also examined the maximal benefit that reorganization can provide to the PAN workload by looking at the execution of PAN-on-Demand with an ideal manager, shown as "After reorganization" in our results.

The key benefit of reorganization is the improved response time for user requests. While PAN members also see some improvement in battery lifetime due to decreased communication route and the characteristic of Bluetooth network that allows the master device to consume 120 mW less than the slaves, these improvements are small and only play a substantial role when the network is heavily used as in the case of photo-sharing application.

8.3.1 MP3 workload

Figure 10 shows results for the MP3 trace execution. Eventhough this workload has a low impact on the manager during data communication as the Bluetooth radio is only being used as a signaling channel for WiFi data transfers, the cost of Bluetooth connections and disconnections has significant impact on the client and server. Thus, a network reorganization is triggered after the 2nd transfer on execution of this workload, making the server the new manager of the PAN.

Compared to a static network topology, reorganization improves the response time by 7% by reducing the latency of one Bluetooth connection for transfers after reorganization. We do not see an improvement in the the battery life of the initial manager and the new manager as the cost of network reorganization is not fully recovered by the members in this trace. When we re-execute the same workload after reorganization, the response time is improved by 16% and the battery lifetime of the members improves by 2–4%.

8.3.2 E-mail workload

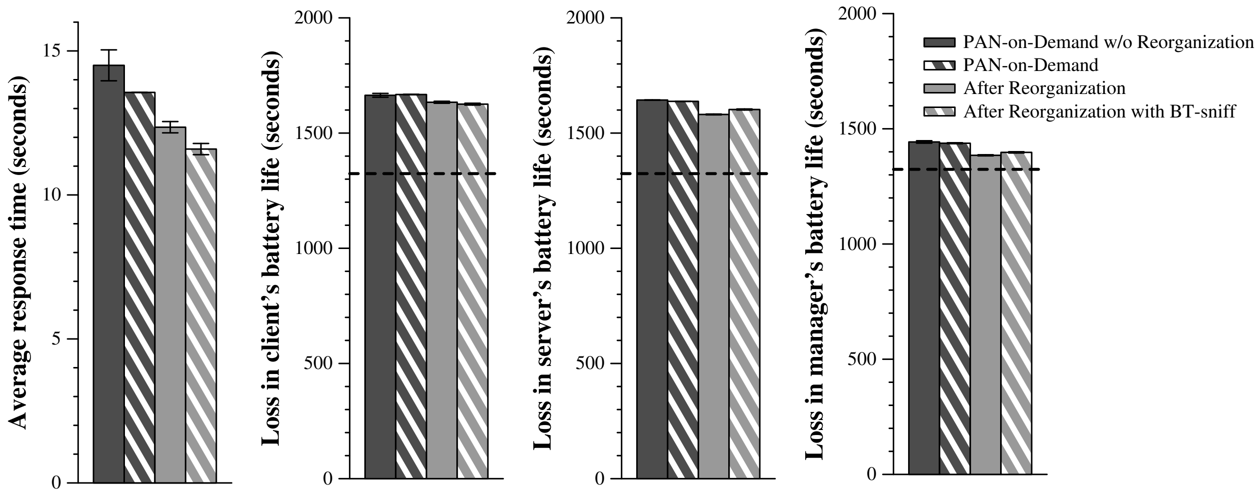
Figure 11 shows results for the e-mail workload. Compared to the MP3 workload, we see more improvement as most of the data transfers are performed on the Bluetooth channel and reorganization reduces the number of hops by half. Network reorganization is triggered on the 4th request causing the 5th request to be delayed by 6 seconds. This results in a reduced benefit with reorganization. We see only an improvement of 10% for the average response time and 2% for the battery lifetime of the members.

Re-executing the workload after reorganization, the average response time of PAN-on-Demand improves by 42% and the battery lifetime of the members improve by 4%. Thus, although reorganization costs mute the benefit of changing the topology during the execution of the workload, the additional benefits that it provides later on are substantial.

8.3.3 Photo-sharing workload

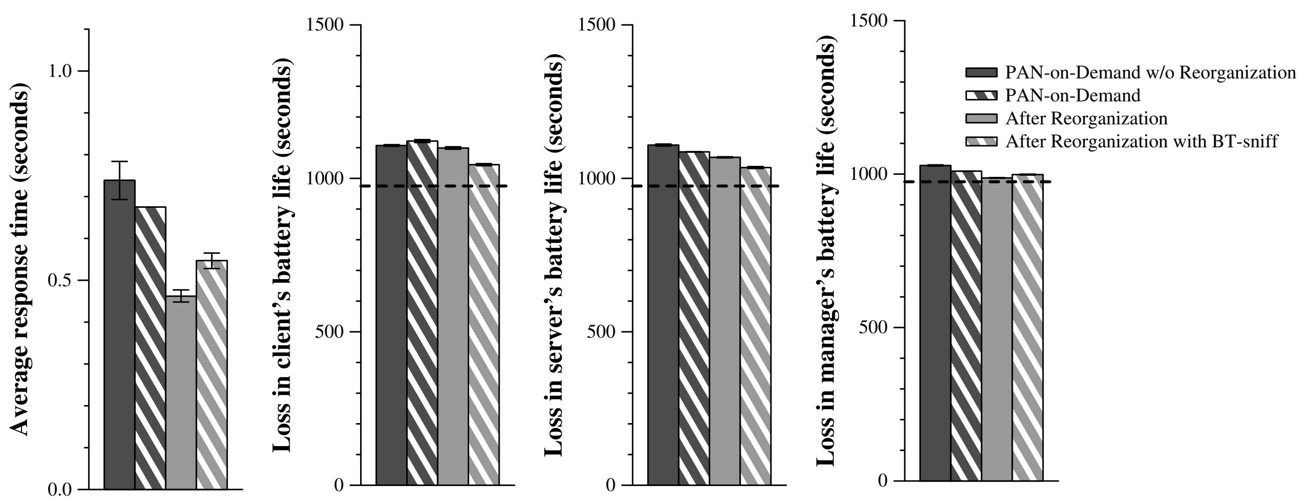
Figure 12 shows results for the photo-sharing workload. Network reorganization is triggered on the 2nd request and reorganization yields a substantial improvement of 38% for the average response time. The battery lifetime of the members improves by 6.5%, 11.5% and 15% respectively for the requester, new manager and initial manager.

Re-executing the workload after reorganization, the average response time of PAN-on-Demand improves by another 25% and the battery lifetime of the members improves by 9%, 15% and 18% for requester, new manager and initial manager respectively.



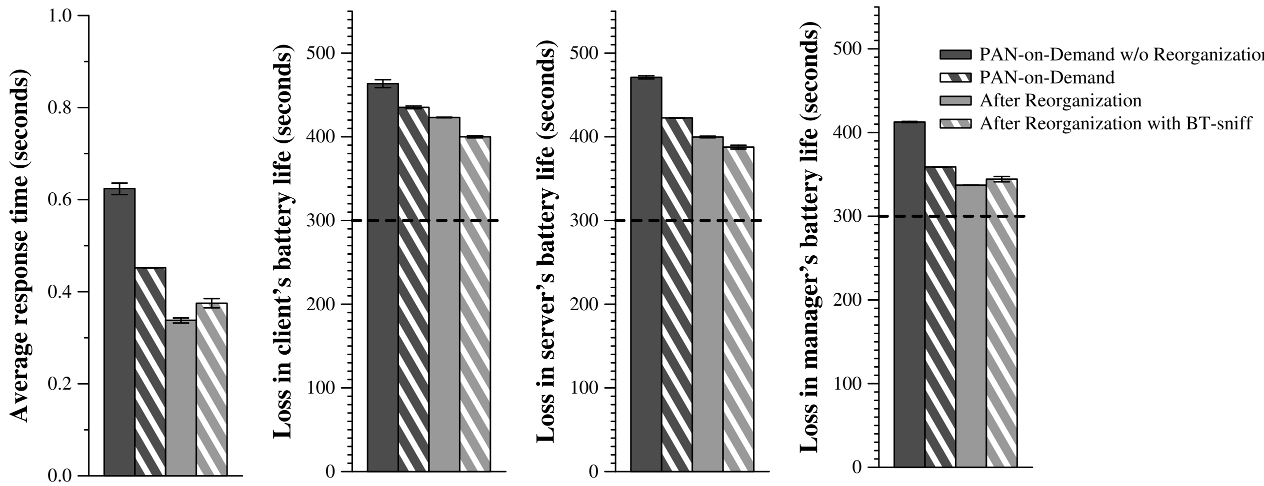
This figure shows the average response time and the impact on the battery lifetime of the client, server and manager for a workload that emulates a user selecting and playing MP3 songs. Dashed line represents the minimal impact that the trace execution will have on the battery life of the members which is equal to 1324 seconds for this workload. Each impact on the battery lifetime value shows the mean of three trials and each average response time value shows the mean of nine trials. The error bars are 90% confidence intervals.

Figure 10. Impact of reorganization and power-saving modes on the MP3 workload



This figure shows the average response time and the impact on the battery lifetime of the client, server and manager for a workload that emulates a user fetching e-mails from a storage device and reading them. Dashed line represents the minimal impact that the trace execution will have on the battery life of the members which is equal to 975 seconds for this workload. Each impact on the battery lifetime value shows the mean of three trials and each average response time value shows the mean of nine trials. The error bars are 90% confidence intervals.

Figure 11. Impact of reorganization and power-saving modes on the e-mail workload



This figure shows the average response time and the impact on the battery lifetime of the client, server and manager for a workload that emulates a user fetching photos from a storage device and viewing them. Dashed line represents the minimal impact that the trace execution will have on the battery life of the members which is equal to 300 seconds for this workload. Each impact on the battery lifetime value shows the mean of three trials and each average response time value shows the mean of nine trials. The error bars are 90% confidence intervals.

Figure 12. Impact of reorganization and power-saving modes on the photo-sharing workload

Initial manager	Reorganize on request	Switch WiFi on request size (KB)
Laptop	1 (2)	83 (107)
iPAQ	7 (11)	109 (150)
Smart phones	16 (33)	124 (198)

This table shows the number of back to back requests for a small transfer (size 6 KB) that are required to initiate a network reorganization when one of the members gets plugged-in. It also shows the size of the request that is required to switch on the WiFi radio. The value in parentheses shows the value when no members are plugged in.

Figure 13. Proactive adaptation

8.4 Impact of additional power-saving modes

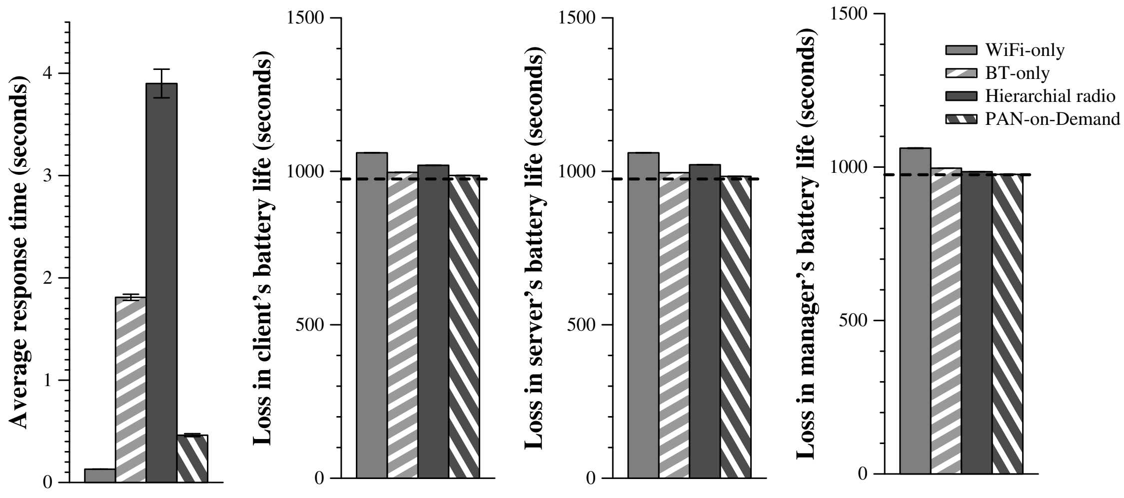
Built-in power-saving modes, such as sniff mode for Bluetooth, provide a potential opportunity to lower the transition cost of switching radios. To study the impact of additional power-saving modes we allowed the Bluetooth radios to employ sniff mode instead of a complete disconnection from WPAN during periods of inactivity. Since the transition cost to sniff mode is negligible, the decision to switch to sniff mode is dominated by the 200 ms performance hit that the requester has to incur and thus PAN-on-Demand enters sniff mode after 2 seconds of inactivity.

Figures 10, 11 and 12 show the result of our experiments. Use of Bluetooth sniff mode improves the average response time by 6% for an MP3 workload where the cost of connection reestablishment plays an important role. In contrast, the use of power-saving mode increases the response time by 18% and 11% for the e-mail and photo-sharing workloads respectively. This is due to the lower cost of transition invoking faster switch from Bluetooth connected to power-saving state to save the overall cost metric that includes both performance and impact on battery lifetime.

Compared to the Bluetooth unconnected state, the use of sniff mode consumes 1% more power that is manifested in increased impact on battery lifetime for the idle devices. The use of Bluetooth power-saving mode reduces the impact on the battery lifetime of communicating WPAN members by 3–5% for e-mail and photo-sharing workload. For an MP3 workload, there is no perceivable improvement.

8.5 Heterogeneity of member characteristics

PAN-on-Demand employs a capabilities based *device list*, as described in Section 5.1, to choose an initial manager of a WPAN. Currently, PAN-on-Demand sorts this list using the base power to choose the device whose battery lifetime will be least impacted in the role of manager. This property is changed when one of the member machine is plugged in to wall power, and this change should be reflected in the structure of the network and interface chosen to perform transfers. In this experiment, we measure the change in the time to perform network reorganization and the transfer size to switch-on the WiFi radios. For our tests, we considered this impact on three different set of devices – laptops with base power of 15.9 W, iPAQs with base power of 1.46 W, and



This figure shows the average response time and the impact on the battery lifetime of the client, server and manager for a workload that emulates a user fetching e-mails from a storage device and reading them. Dashed line represents the minimal impact that the trace execution will have on the battery life of the members which is equal to 975 seconds for this workload. Each impact on the battery lifetime value shows the mean of three trials and each average response time value shows the mean of nine trials. The error bars are 90% confidence intervals.

Figure 14. Benefit of PAN-on-Demand for the e-mail workload with laptop members

a low-power smart phone with base power of 250 mW.

Figure 13 show the impact on PAN-on-Demand characteristics with different devices as members. Our results demonstrate that PAN-on-Demand handles the change in device characteristics quite effectively. PAN-on-Demand calculates the impact that reorganization will have on the current members of the WPAN and adjusts the time to reorganize accordingly. Reorganization is performed more frequently with more capable members, like laptops, where the battery lifetime cost of reorganization has little impact and the opportunity cost of performance dominates. In case of less provisioned members like smart-phones, PAN-on-Demand is more conservative. PAN-on-Demand behaves similarly while choosing the break-even size for WiFi transfers.

Figure 14 shows the result of executing the e-mail workload on a PAN consisting of only laptops as members. PAN-on-Demand recognizes the change in member characteristics and immediately reorganizes after the 2nd transfer to improve the average response time. Compared to WiFi-only, PAN-on-Demand adds 330 ms to the average response time and saves 74–82 seconds of battery lifetime for its members. Compared to BT-only, PAN-on-Demand improves average response by 1.35 seconds while saving 10–12 seconds of battery life. Compared to the hierarchical strategy, PAN-on-Demand improves the average response time by 3.5 seconds and battery life by 6–37 seconds.

9 Related work

To the best of our knowledge, PAN-on-Demand is the first system to dynamically adapt the choice of wireless interfaces and network topology in a personal-area network in response to application demand. It differs from previous research in personal-area networks in that it considers both performance and energy conservation in its algorithms.

Contact Networking [5] allows two mobile computers to continuously communicate with each other while switching between different network interfaces. Switching policies in Contact Networking are motivated by the connectivity requirement of applications and hence they employ a static hierarchy based on the communication range of each interface. In contrast to PAN-on-Demand which adaptively chooses the best interface to use based on performance and energy considerations, Contact Networking always chooses a low-range interface such as Bluetooth in preference to a wider-range interface such as WiFi.

Similar to PAN-on-Demand, CoolSpots [16] and PPM [18] also employ policies to switch between different wireless interfaces to improve device power management. CoolSpots and PPM choose the wireless interface with least power consumption to communicate, given that the performance requirement of the applications are met. Unlike PAN-on-Demand, they focus only on the reduction of energy consumed by the network interface on a device and are not directly applicable to a

PAN with more than two members. Furthermore, they also do not deal with device discovery, routing, or the topology of the network.

MOPED [4] allows a mobile computer to aggregate transmission bandwidth across multiple non-interfering wireless channels. Aggregation is not a good choice in the PAN-on-Demand environment since Bluetooth and 802.11b (WiFi) transmissions interfere with each other [7, 10]. Multiplexing data transmissions across the two interfaces would decrease throughput and increase energy usage in our environment.

Pering et al. [17], Wake-on-Wireless [20], and the Turducken project [22] have previously explored using low-power radios to signal mobile computers to activate high-power radios. Our experiments show that the hierarchical radio strategies often perform poorly, when the PAN is actively used, due to the overhead of enabling and disabling the high-power radios.

Leopold et al. [12] explore the suitability of Bluetooth for sensor networks. Their work notes that maintaining Bluetooth connections is an expensive operation. They conclude that network assembly should be rapid and energy-efficient. Similar to other research on sensor networks and Bluetooth scatternets [13, 15, 19], the focus of their work is on multi-hop communication where routes can be much longer than the two-hop maximum of PAN-on-Demand.

10 Conclusion

PAN-on-Demand has three goals: maximize performance, extend battery lifetime, and minimize user distraction. Our experimental results show that it does a good job of meeting these goals for MP3, e-mail and photo sharing workloads. The strategies PAN-on-Demand uses to achieve these results are:

- **self-organization.** Nodes discover each other without user involvement. Users do not need to explicitly initiate communication at each endpoint of the system.
- **adapting the network topology.** Nodes that are actively communicating are more likely to be the manager at the hub of the network. This improves performance and saves energy by shortening routes.
- **choosing the right route and set of interfaces.** For each data transfer, PAN-on-Demand adapts its communication strategy to match the size of the expected transfer and the current state of network interfaces throughout the PAN.
- **proactive mode transitions.** Interfaces are disabled and connections are dropped to save power during idle periods. Interfaces are re-enabled when many small transfers in the near future are anticipated.

Building on these results, we see several directions for future work. We plan to explore the opportunistic use of infrastructure support when available. If a PAN manager notices a nearby base station, it can trigger a switch to infrastructure mode so that all members communicate via that base station. Fixed infrastructure can reduce the energy expended by PAN devices since they can employ power savings mode currently unavailable in ad-hoc environments. We also plan to investigate the impact on wireless interference on personal-area networks. A PAN manager could potentially direct its workers to use non-interfering channels and/or network technologies to maximize the throughput of the network. We believe that PAN-on-Demand provides a promising infrastructure on which to explore these and other issues.

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