Abstract

In order to support connectivity requirements for today's pervasive devices, a new type of wireless network is needed. Pervasive Information Network (PiNet) is a new wireless connectivity architecture designed to support access to organizational information using lightweight handheld devices. PiNet's main objective is to support a mass-market-type application, where thousands of users can simultaneously have interactive access to a variety of organizational information sources while maintaining a short response time and using a simple, low-cost, power-limited pervasive device. This article summarizes the necessary characteristics of PiNet and presents a survey of the existing main technologies, explaining how they fall short of providing a total solution for pervasive wireless networks. In conclusion, this document indicates the direction that must be taken in order to design a solution that will provide a large number of users with a practical means of obtaining information in a timely manner.

PiNet: Wireless Connectivity for Organizational Information Access Using Lightweight Handheld Devices

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In recent years two unrelated trends have stood at the forefront of technology. First are the great improvements in the accessibility of information which, driven by the Internet revolution, have made it possible to access huge amounts of information using a traditional PC and simple browser. Second are the advancements in computer technologies which reach beyond the traditional desktop environment to areas such as mobile, or even wearable, computing. A clear need has emerged, to allow these handheld devices access to personally relevant information from a variety of sources. The problem is how to enable mobile handheld devices direct zero-configuration access to the tremendous amount of available information. Present-day solutions are based on standards developed for a different set of requirements and needs. In order to build a suitable infrastructure that supports simultaneous access by thousands of low-cost resource-limited mobile devices, a new approach and a new set of protocols and standards must be developed.

Pervasive Information Network (PiNet) is designed to provide the connectivity requirements for large-scale personal information knowledge systems (PIKS). The IBM Haifa Research Lab (HRL) does continuous research in the area of PIKS, with the objective of providing a wide range of information and services to people who are moving within a defined area. PIKS can be deployed in a variety of places such as airports, theme parks, malls, hospitals, museums, or any other large campus where arbitrary visitors need immediate access to information. In a theme park, for example, visitors would use PIKS to find suitable attractions, the location of the attractions, and the queue status.

PIKS is designed to replace existing information sources such as information desks and bulletin boards, and to improve access to the existing, and new, organizational information. The main advantage of PIKS is that the user only receives the relevant requested information.

PiNet, a new wireless connectivity infrastructure, was designed and developed to support PIKS-like applications. PiNet builds on the future pervasive availability of small, handheld, low-cost devices used for a variety of purposes such as finding flight information at an airport, obtaining the floor plan at a museum, or locating a desired attraction in the surrounding area. PiNet is designed to support a large number of concurrent users while maintaining a reasonable subsecond delay per interaction, for individual user response times. PiNet architecture incorporates an optimal blend of efficient server exploitation, minimal network messaging, and limited handheld device resources to provide a cost-effective solution for widescale deployment.

The following section provides an in-depth description of PiNet requirements needed to support PIKS, followed by a brief description of existing connectivity solutions and their limitations. The final section presents a set of guidelines and a working prototype, which we believe will lead to the best connectivity solution for PIKS-like applications.

Architecture of a Pervasive Information Network

PiNet is a client/server connectivity architecture designed to satisfy the mass market. PiNet assumes that thousands of novice users will attempt information retrieval in an unfamiliar environment. PiNet is essentially a network architecture, but in order to deepen the understanding of the system we will begin by giving a short description of the client/server model used by PiNet.

PiNet Client/Server Model

Mobile client/server systems are primarily distinguished from one another in the application partitioning model [1]. The

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client side design is the main aspect in which the PiNet model differs from similar systems, such as PARCTAB [2] and InfoPad [3]. In order to be used as a pervasive device, the client is expected to be very small in size and highly efficient in power consumption. A touch screen with smart-card form factor armed with a tiny integrated transceiver is a perfect target device. Such a device can always be carried in everyone's purse, and used whenever needed. Although personal digital assistants (PDAs), smart phones, and other handheld devices could be used as clients for PiNet, we believe it is critical to success in the pervasive world that "low-end" clients may also be used. Such clients, which are not on the market yet, are expected to be smaller in size, consume less power, and cost much less.

In the PiNet architecture, the information and applications are located on a central scalable server, while a small generic kernel running on the user's device supports user interaction. Information screens and interactive objects are sent to the user's device over PiNet as needed, without any preloading or site-specific configuration. To enable information parsing, only the ultra-thin generic client kernel must be preinstalled on the device.

Connectivity Requirements for PiNet

To best support personal access to information by arbitrary visitors, a set of requirements must be met. The need for good connectivity support for unregistered anonymous users introduces a new challenge to network requirements. The following requirements must be implemented in PiNet architecture:

- **Power conservation**: Users in the mass market expect their appliances to work for weeks or even months without having to replace the battery. PiNet must be able to support efficient power conservation modes. It is desirable that the device be able to work for months without battery replacement or even work without a battery at all, using, for example, solar cells as an external power source.
- **Small size**: To be accepted by mass market users and encourage use of the application in everyday scenarios, the client's device must be very small in size.
- **Transparent connection**: A completely transparent connection, with zero configuration requirements, is a must. When entering an area covered by PiNet, the user is expected to turn on the device and be automatically connected. No configuration changes are necessary as the user moves from one organization to another. The network needs no preknowledge regarding the device attempting to connect to it.
- **Serve many users**: In some extreme cases, organizations may want to accommodate thousands of users concurrently. PiNet must be able to serve thousands of connected devices in an acceptable response time.

To enable efficient and easy access to information, some additional network requirements must be met, such as:

- **Fast response time**: The response time for user interaction must remain in the order of hundreds of milliseconds.
- **Transparent roaming**: While using the application, the user is expected to roam within the network's coverage area. Changes in location must be both transparent from the user's point of view and without data loss.
- **Location awareness**: Awareness of the user's location enables the application to supply the user with the information relevant to a certain location.
- **Robust connection**: As in most data applications, a reliable, error-free link between the device and the information source is mandatory. Error detection and correction must be transparent to the user.

Using Existing Wireless Solutions

In our attempts to build PiNet connectivity, existing technologies and standards must be examined. Many standards exist in the area of wireless communications. While we cannot cover all of them, below is a brief description of the main activities in wireless communications along with their advantages and disadvantages for personal information access by mobile users. This section examines three areas: IEEE 802.11 wireless LAN, Bluetooth, and mobile telephone systems (MTS).

IEEE 802.11 Wireless LAN

The IEEE 802.11 committee has defined a standard for wireless LAN [4]. The standard supports both ad hoc networking, in which peer nodes communicate directly, and infrastructure networking in which nodes called access points (APs) are interconnected over a distribution system. The wireless LAN standard includes a medium access control (MAC) layer, which is intended to operate over multiple physical layers. The MAC layer defines a random-access-type protocol to access the channel. It is part of a larger system architecture that defines station synchronization and power management functions as well as authentication and reassociation services to support roaming. The 802.11 standard was designed as a wireless extension for LANs. Advanced protocols such as RTS/CTS are introduced to reduce the loss of bandwidth, which is caused by collisions on long frames due to hidden stations. Less attention was made to supporting small, simple mobile devices to efficiently utilize the distributed network.

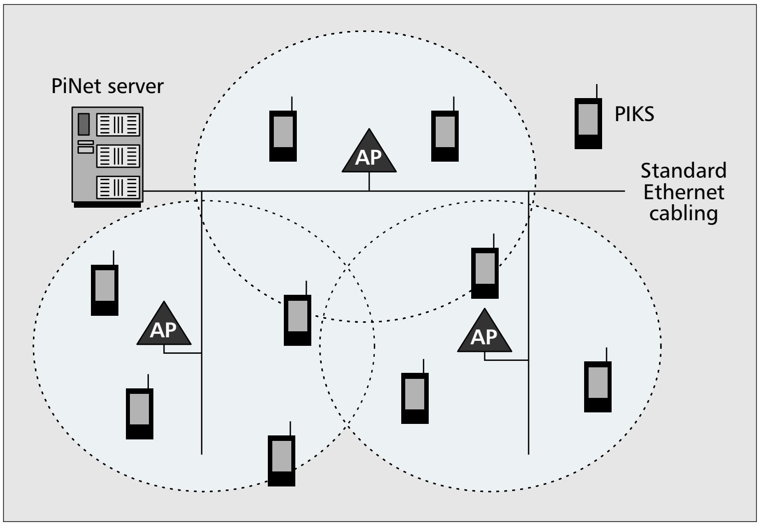
Wireless LAN implementations require continuous connection to the network and are therefore inefficient in power utilization. Although power conservation modes exist, even advanced implementations can only work up to 12 hr before the battery must be recharged. Another disadvantage is that wireless LAN devices are very expensive and large in size.

In conclusion, the wireless LAN standard is overkill for PiNet needs. Its power consumption, price, and size are inappropriate to serve as small, inexpensive mobile devices.

Bluetooth

Bluetooth is a standard for low-cost, low-power, radio-frequency connectivity for various devices, such as PDAs, cellular phones, and other cost-sensitive information appliances [5].

Bluetooth was originally designed to enable mobile devices, in proximity with each other, to establish an ad hoc cell called a *picocell* and exchange information. Every picocell has a master unit that controls traffic between up to seven slave devices in the cell. The master can also be a stationary unit that establishes a cell and waits for the mobile device to come into proximity and connect. Bluetooth has poor built-in support for a distributed network. Bluetooth scatternet architecture, where a number of picocells form a larger network, was introduced to overcome this shortage. The main problem with this architecture is the long synchronization time a mobile device requires in order to reconnect to new cells. Bluetooth cells are small in size (a theoretical radius of 10 m), and a roaming user is expected to change picocells every 10 s. Searching for a new picocell and registering in it is a power and time (several seconds) consuming process. An additional Bluetooth limitation is the polling scheme architecture used at the MAC level. In each time slot, the master gives one of the connected slaves permission to access the channel. The PiNet world assumes that many devices exist in the cell coverage area, but only a small portion of them are active at any given time; hence, trying to poll information from all of them in a round-robin fashion is inefficient. Although Bluetooth also defines a random access MAC working mode, this is an esoteric feature of Blue-



■ **Figure 1.** *General architecture of a cellular PiNet network.*

tooth and is not planned to be implemented in the first stages.

To save power, slaves can go into park mode, where they do not participate in the polling cycle; however, they must still remain synchronized with their master, and cannot completely shut down their transmitter. In addition, the procedure of putting a slave into park mode or making it active is a power, time, and bandwidth consuming process, especially if it needs to take place many times every second.

In summary, Bluetooth was primarily designed for an ad hoc network with the participation of a limited number of devices within a limited working space. It is not designed to allow access to information by a large number of mobile users who roam freely within a large network coverage area.

Mobile Telephone System

Mobile telephone systems are widely used all over the world. The penetration of cellular phones into the marketplace has been incredibly fast and continues to grow. An MTS is a wide area network (WAN) in nature and is meant to be able to supply coverage for wide areas with an assumed distance of a few thousand meters between the mobile unit and the base station [6]. Such an assumption has a major effect on the device's power consumption as well as the network's bandwidth capabilities. MTS successfully enables many users to be connected by using a cellular architecture, which allows for reuse of frequencies.

Allowing access to organizational information over public MTS lines has some major drawbacks from the user's perspective: the round-trip delay is high (more than 10 s), the user is charged for each interaction, and the connection phase is not transparent since the user must dial a different phone number for each organization. One solution is for the organization to install a private cell, a new wireless architecture technology supplied by some MTS companies allowing for free private communication within the organization's wireless nodes. Installing a private cell allows an organization to supply visitors, as well as workers, with free connection to its information sources. Even if a private cell is used, MTS is still a closed environment in terms of spectrum and system architecture. In most cases, the infrastructure is owned or maintained by the MTS company itself. There is no off-the-shelf solution for an organization to install an independent private cell. Furthermore, most protocol implementations over MTS support voice transmission. Using MTS to access organizational information and other data services faces some serious problems and is still in its early stages.

In summary, MTS architecture in general, and private cell architecture in particular, could be used by organizations to supply access to information sources. The current implementation, however, which operates in a closed environment controlled by telephone companies, puts major limitations from both the user's and organization's points of view.

Comparison of Connectivity Solutions

Table 1 compares the characteristics of existing connectivity solutions to those required by PiNet.

Requirement	802.11 Wireless LAN	Bluetooth	Mobile telephone system (MTS)	Optimal for PiNet
Power conservation	Hours	Days	Days	Months (long as possible)
Small size	Medium	Small	Medium	Small as possible
Transparent connection	Low (some network configuration is required)	High	Medium (dialing a number)	High as possible
Low cost	No	Yes	Medium	Low as possible
Serve many users	Good	Limited (up to 7 in each cell)	Good	Dozens in each cell
Fast response time	Good	Good	Poor (long round-trip delay if public network is used)	Subseconds
Transparent roaming	Yes	No (very long synchronization time)	Yes	Yes; without performance reduction
Location awareness	Medium (medium-size cells)	High (small cells)	Low (large cells)	Smaller cells provide better awareness
Bandwidth	Very high	High	Modest	Modest (tens of kbytes per channel)

■ **Table 1.** *Characteristics of existing connectivity solutions and those required by PiNet.*

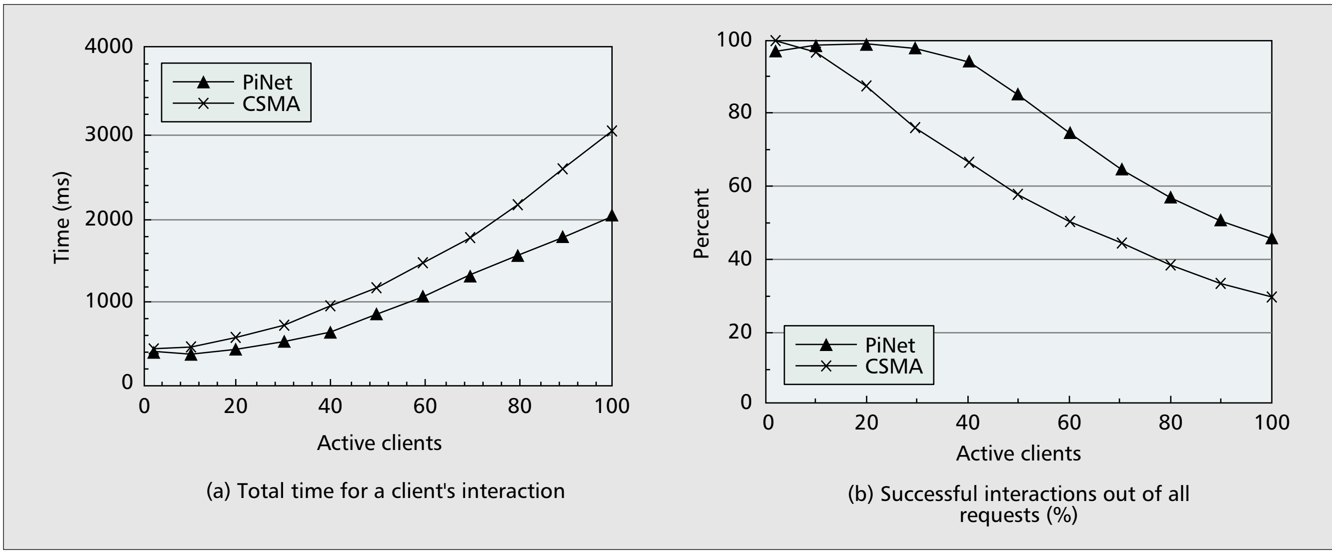


Figure 2. *Simulation results of the PiNet MAC protocol compared to classic CSMA.*

The PiNet Solution: Asymmetric Cellular Wireless Network

We have compiled guidelines for what we consider the optimal solution for PiNet based on the list of requirements presented earlier and the advantages and disadvantages of existing technologies. In the next sections an overview of the cellular network is presented followed by a detailed description of a MAC protocol within a single cell. To complete the picture, a list of possible solutions is described to allow efficient operation of the multicell architecture.

Cellular Network Architecture

Our PiNet solution is based on cellular network architecture [6]. Cellular networks enable many devices to use limited frequency spectrum resources, which increase the overall bandwidth capacity. Each cell has an access point (AP), which is the control point of all traffic within the cell. The cell's size can be designed according to network requirements. Picocellular architecture, where the cell's size is 10–20 m, is most suitable for PiNet. Reducing the cell size has the advantage of allowing more cells to coexist in a given geographical area, leading to better frequency reuse and an increase in network capacity. Reducing the cell size also means that transmission power can be dramatically reduced and location awareness improved. In contrast to these advantages, handoffs (the procedure where a user must change from one AP to another) occur more often in a picocell architecture, requiring a robust and efficient handoff mechanism.

PiNet architecture primarily deals with the wireless connection between the clients and the AP, and relies on conventional wired or wireless connection between the AP and the server. Figure 1 presents the general architecture of PiNet.

MAC Protocol for a Single Cell

As a solution for personal information access, PiNet assumes asymmetric traffic on the upstream (from client to server) and downstream (from server to client) channels. Upstream traffic comes from several asynchronous clients, with each client producing a very short message. Downstream traffic emanates from a single source, producing long messages. Our implementation shows that an upstream client's information request message averages 20 bytes, while a downstream information response averages 300 bytes.

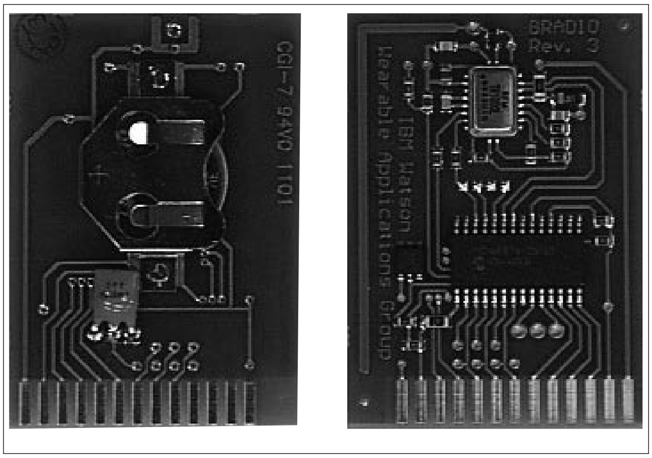
Bandwidth requirements for PiNet are modest in nature due to the short messages and small cell size. Experience shows that an active user utilizes an average of 100 bytes/s. Assuming 10 percent of users are active, even in a crowded area (e.g., an airport or a shopping mall), only about 20 kb/s must be successfully transmitted in each cell. Even when adding channel overheads and considering channel utilization, we still end up with modest bandwidth requirements.

Upstream MAC Protocol — All clients in a cell use the same upstream frequency. A carrier sense multiple access (CSMA) protocol [7] is most suitable for managing the channel, since many clients are able to utilize the channel, but only a small portion of them do so at any given time. After sensing the media and choosing a random time to start transmission, each client is free to transmit. If transmissions from two or more clients collide, some collision resolution protocol takes place. No complicated collision avoidance protocol is needed because all upstream messages are short.

Downstream MAC Protocol — Downstream messages are an order of magnitude larger than upstream messages. It is therefore desirable to protect them from collisions. Two methods may be considered. One is to allocate different frequencies to downstream channels, requiring a more complicated transceiver. The other is to protect a downstream message by attaching an unused preamble with a duration equal to that of a single upstream message (about 10 percent overhead). This way, upstream messages collide on the downstream preamble, while downstream data can still pass through. The server uses the preamble technique for load control. An AP can transmit a server's response whenever needed, knowing that the data portion of the message is not going to be corrupted by upstream messages.

Simulation

We simulated our MAC protocol using the preamble technique for the downstream and a CSMA protocol for the upstream. We simulated user interactions with an information source where the average user request is 20 bytes, the average server's response is 500 bytes, and the server's processing time is 300 ms. The simulation results in Fig. 2 are for a 33,600 kb/s wireless link between the clients and the AP. As we can see, despite the moderate bandwidth, PiNet can comfortably support up to 50 active users in a single cell, while maintaining a reasonable response time (Fig. 2a) and minimal message loss (Fig 2b). We assume that support for 50 active users is adequate for heavily crowded places.



■ **Figure 3.** *A simple narrowband transceiver.*

■ **Figure 4.** *Examples of application screens: a) data query; b) location-specific information.*

Integrating Many Cells

A classic cellular network uses different frequencies between adjacent cells [6]. Frequency reuse can be done between nonoverlapping cells. On such networks, clients must change frequencies while roaming between cells, which adds some complexity to the client's transceiver. Another method uses an external synchronization mechanism to prevent adjacent AP collisions. This mechanism could be based on static time division between APs or some dynamic token protocol running between them. Additional solutions such as a combination of time and frequency division may also be considered. An important point is that the upstream channel frequency can be common to all cells. Our MAC protocol already assumes collisions on the upstream channel and features a recovery mechanism. This network characteristic improves the handoff procedure because it eliminates the need for upstream synchronization.

Meeting Other Connectivity Requirements

Power Conservation — A request-response-like protocol was developed to meet the need for efficient power conservation. When the device transmits a message, the transceiver moves into active mode until the response message is received from the server. Once the server message is received without errors, the client's transceiver is turned off. The server is not allowed to send unsolicited messages to a client. To allow the server to maintain an open connection with a client, the server can add a *keep alive* timer to its response, asking the client to set that timer. When the timer expires, a message is sent from the client to the server, enabling the server to send updates to the client and, if desired, to request that the client reset the keep alive timer.

Transparent Connection — To enable a transparent connection, no server address is defined. All client messages are broadcast messages. An AP that receives a message from a client passes it on to the server. The server has the ability to filter redundant messages from the same client through different APs. The response to the client is sent through the AP that received the request.

Location Awareness — Knowing through which AP a message arrived allows the server to define which cell the device is currently connected to and therefore know its approximate location. Using a small cell size allows us to get accurate location information.

The Prototype System

We have implemented a working PiNet prototype based on a simple narrowband transceiver (Fig. 3). The transceiver has a serial interface through which it receives data that is being sent from the device to the air interface and transfers information received from the air interface back to the device. No other MAC functionality such as framing, error detection/correction, or retransmission is available from the transceiver. We connect the transceiver to an IBM WorkPad through the serial interface. For each AP, we connect a similar transceiver to a PC serial port. The MAC layer protocol is implemented in software. The software gathers bytes into frames, adds a client's unique address, a sequence number, and a 16-bit cyclic redundancy check (CRC). Upon receiving a frame, the client address, sequence number, and CRC are all checked to decide whether the frame is a legal valid frame.

Our protocol works as follows:

- Client: Create a new frame for each user information request.
- Client: Turn on the transceiver and send the frame as a broadcast frame toward the distributed network.
- AP: The frame is received and passed on to the server.
- Server: A response is sent back to the client through the same AP that received the request.
- Client: Upon receiving an error-free response from the server, the client turns off its transceiver. If no response is received within the timeout period, the client resends the request.

Usage of the Current Prototype

Our current prototype has no support for AP synchronization; all transceivers operate on the same frequency. Nevertheless, we were still able to cover a large multiroom office environment with several APs. We used several mobile devices and were able to roam freely in the coverage area while interacting with relevant organizational information such as the personnel directory, an address book, a relevant acronyms list, a lunch menu, and important events. Figure 4a shows a typical user interaction, a data query, with the PIKS client. Our system is also able to track a user and supply him/her with location-dependent information such as the location of the nearest restroom or available conference room (Fig. 4b).

Our prototype system's client device is very efficient in its power consumption because it shuts down its transceiver immediately after receiving a response from the server. Our client device, powered by a small off-the-shelf battery, can request and receive about 4000 screens of information from the server. We estimate that an active user will view at most 4000 screens a month.

Our prototype also features a completely transparent connection. No action is required from the user to connect and retrieve information. The user taps the application icon on its device and the first information screen is displayed. There is no need to supply addresses for either the user's device or the server.

Conclusions and Directions for Future Work

Having described the requirements for PiNet, the need to implement this set of requirements in a working hardware model is clear. Many standards exist and others are being developed, but none of them fulfill all PiNet requirements. PiNet hardware, like other communication solutions, must be standard in order to interoperate with other hardware of the same type. The perfect PiNet client is a smart card form factor client with a touch screen, simple and inexpensive microcontroller, and transceiver. We are working toward implementing such a device. A good power conservation scheme is essential for mass deployment in the consumer market. The concept of a device that can go for months without battery replacement, or even completely without a battery (e.g., using a solar cells) is a challenge that can be overcome in the near future.

No research currently exists regarding the usage model of PIKS-type applications. We believe this kind of research must take place in order to provide us with a better understanding of the exact PiNet requirements for bandwidth, acceptable response time, and the implementation of an optimum MAC protocol.

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