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Personal Mesh: A Design of Flexible and Seamless Internet Access for Personal Area Network

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SUMMARY   With the proliferation of various types of computing and networking resources in ubiquitous computing environments, an architecture allowing mobile users to flexibly access these resources is desirable. We have focused our attention on the access link resources of devices surrounding users. Our framework named Personal Mesh allows personal devices to seamlessly access the Internet via appropriate access links available in a personal area network. The Personal Mesh deals with two technical issues: access link selection management and a PAN mobility support mechanism. In this paper, we describe the design and implementation of Personal Mesh and show the effectiveness of our system by experiment.
key words: *personal area network, Internet access link, mobility support, personal gateway*

1. Introduction

In ubiquitous computing environment [1], computing and networking resources will appear in various kinds of devices in the area surrounding users. The cooperation among these devices is essential since it enables the resources to be shared and used efficiently. The emergence of short-range low-power wireless communication technologies such as Bluetooth [2] now enables device cooperation in a new type of network called a personal area network (PAN).

Our work focuses attention on the sharing of Internet access link resources (i.e. Internet connections of devices) within the PAN of a mobile user. In a PAN, several kinds of access link resources with different access technologies such as wireless LAN and 4G may appear and their performance may differ in bit rate, packet cost, coverage area, power consumption. Mobile devices' Internet connection quality can be improved by sharing access link resources in a PAN. First, the Internet connection area of mobile devices can be expanded. For example, a mobile device which has only a short-range wireless link can access the Internet via a wide-area access link of other devices in the PAN. Second, since one bottleneck link on the end-to-end communication path of personal devices is on the wireless access link, Internet connection quality can be improved through the utilization of appropriate access links for each communication session, which meets the application's performance requirements and the user's preferences.

One characteristic of PAN is the dynamic change of its access link resources due to user movement. The change includes the change of PAN topology (i.e. the arrivals/departures of devices), the change of access link status (e.g. up/down) and the change in the point of attachment to the access network. For long-term communication sessions such as streaming sessions, file download sessions, etc, the probability of a change during a communication session will be high. If there is not a mobility support mechanism to support the change, such change of access link resources may cause the interruption of communication or the use of an inappropriate access link. Mobility support for a mobile host/mobile network has been the subject of much research [4]–[10]. However, to the best of our knowledge, little research has performed on the appropriate use of access link resources and mobility support in PAN environments where access link resources change dynamically.

We have developed a framework, called Personal Mesh, which allows devices in a PAN to use appropriate access links for their communication sessions without interruption even when access link resources in PAN change dynamically. Our framework is realized by a software module installed on devices that have at least one Internet access link. We call such a device a Personal Gateway (PGW). Our design does not require local devices (i.e. devices that have only short-range wireless link) to be aware of the change in access link resources.

The main contributions of our work are as follows:

- Design of an access link selection management scheme which allows PGWs to select appropriate access links for communication sessions of PAN devices. PGWs handle information regarding access link resources, devices' session communications and access link selection policies in a distributed manner, allowing the system to adapt to dynamic changes in access link resources as well as device arrivals and departures.
- Design of a PAN mobility support scheme allowing PGWs to maintain communication sessions of PAN devices when a change of access link resources occurs. Our scheme is realized by message exchange between PGWs and the use of binding update and address/port translation at PGWs and corresponding hosts. It allows devices in a PAN to freely switch each of their communication sessions to an appropriate access link without communication interruption.

We have implemented a prototype of Personal Mesh and

have proved the effectiveness of our system by experiment.

The rest of this paper is structured as follows. We describe our basic design in Sect. 2; describe our implementation including Personal Mesh's system structure and its operations in Sect. 3. Section 4 describes our testbed network and our experimental results. We discuss related works in Sect. 5 and conclude the paper in Sect. 6.

2. Personal Mesh

2.1 Application Scenarios

Figure 1 shows one of our application scenarios. In this scenario, the PAN of a mobile user contains a headset, a wristwatch, a mobile phone and a PDA, all of which are Bluetooth-enabled. In Fig. 1a), as the user walks down the street, his headset, wristwatch and PDA use the mobile phone as a PGW to access to the Internet. The communication of the three devices is maintained when the mobile phone changes its attachment point to the access network. In Fig. 1b), when he enters a wireless LAN hotspot, the wireless LAN of the PDA comes up and the PDA becomes another PGW of the user's PAN. In this case, the headset and the PDA continues using the QoS-provided mobile phone for their voice and video communication respectively, but the data communication sessions of the wristwatch and PDA are switched to the low-cost high-bit-rate non-QoS provided wireless LAN. In Fig. 1c), when he comes to the office, the desktop PC is added to his PAN and acts as a new PGW of PAN. In this case, all three devices switch to use the low-cost, high bit-rate, QoS-provided Ethernet LAN.

The above scenario illustrates the flexible Internet access of devices in a PAN as a mobile user roams. Personal Mesh allows each device to adapt to the change of access link resources in the PAN by using an appropriate access link for each of its communication sessions. Practical realization of Personal Mesh requires us to solve the following design and implementation problems.

First, appropriate access link must be selected for each communication session of devices in a PAN when access link resources in the PAN change dynamically. For example, in Fig. 1b), the wireless LAN of PDA is selected to use for the wristwatch and PDA's data communication sessions instead of the mobile phone. Different access links may be selected for different communication sessions according to each application's Internet connection quality requirements and user preferences.
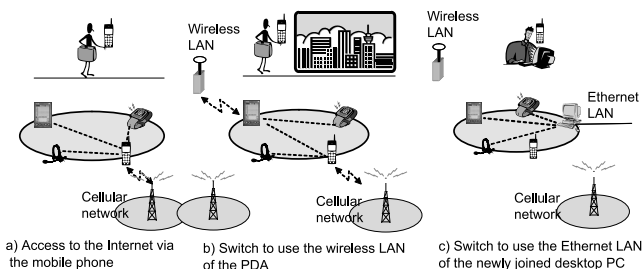
Second, communication sessions of PAN devices must be maintained in the case of horizontal handoff, access link handoff and vertical handoff. We call this issue PAN mobility support. Horizontal handoff occurs when a PGW, such as the mobile phone in Fig. 1a), changes its attachment point to the access network. In this case, not only the PGW but other devices that access the Internet via the access link will also have to change their network location. Access link handoff occurs when a PAN device switches its communication session between access links of different PGWs, such as when the wristwatch and PDA switched to use the wireless LAN in Fig. 1b) or when the wristwatch, PDA and headset switch to use the Ethernet LAN in Fig. 1c). Vertical handoff is similar to access link handoff but the switch of a communication session is between access links of the same PGW. In both access link handoff and vertical handoff, the PAN device will change the access network that transfers packets for its communication session and therefore change its network location.

Given that IP communication will be common in ubiquitous computing environments, we assume that devices in a PAN can communicate with each other via IP and construct a broadcast domain. In the next subsections, we will describe the design of our Personal Mesh.

2.2 System Design

We consider three viewpoints for the design of Personal Mesh. First, local devices such as the headset and wristwatch, which have only a short-range wireless link, may not be aware of PAN's mobility. In ubiquitous computing environments, such devices will be used broadly for specific purposes. It is impractical to install additional access link selection function or mobility support function on them because of their limited expansion capability and their limited computing power. Hence, PGWs which stand at the boundary of a PAN and the global network (Fig. 2) should provide flexible Internet access service to all PAN devices.

Second, a PAN device such as the PDA in Fig. 1b) may create multiple communication sessions with a correspond-
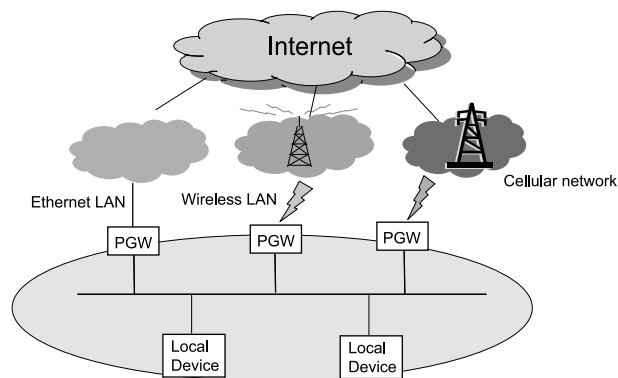

Fig. 1 Application scenarios of Personal Mesh.

a) Access to the Internet via the mobile phone

b) Switch to use the wireless LAN of the PDA

c) Switch to use the Ethernet LAN of the newly joined desktop PC

Fig. 2 Personal Mesh.

ing host and different access links may be selected for each session in order to meet different Internet connection quality requirements (e.g. delay-sensitive or bandwidth-sensitive). To allow the PAN device to switch each communication session to an appropriate access link, the session information (i.e. address/port pairs of sender and receiver, and the type of transport protocol) should be used to identify a session for the packet forwarding.

Third, a PGW may be disconnected from PAN. In this case, another PGW must instead perform the processing of mobility support to maintain communication of PAN devices. Hence, the processing of mobility support must be able to be migrated between PGWs.

The basic NEMO protocol proposed by IETF NEMO working group maintains communication of a mobile network through the use of home agents in the global network to forward packets to the mobile network. However, an extended version of NEMO protocol is necessary to adapt to the above requirements. First, home agents must be able to forward packets based on not only the destination address but also the session information. Second, mobile routers (i.e. PGWs) in the mobile network must be able to be associated with each of their home agents to realize the migration of the processing of mobility support. We take a different approach from NEMO for PAN mobility support in that we move the mobility support function to the end hosts (i.e. PGWs and corresponding hosts) instead of relying upon home agents in the global network. Hence, the access link handoff can be easily and freely achieved by the cooperation between PGWs and corresponding hosts.

The main points of our design are as follows.

First, PGWs select appropriate access links for each communication session of each PAN device passing through it. The selection is based on access link information, application requirements and user preferences. PGWs cooperate with each others to gather required information. They also observe access link resource changes. Whenever an access link resource change occurs, they reselect access link and trigger a handoff if necessary.

Second, PGWs maintain addresses of devices in PAN unchanged through the use of an address/port translation function. This function is an extended version of the address/port translation function of a NAPT's box [12], modified for the use with a PAN mobility support scheme to be mentioned later. Every PAN device is assigned a private address when joining the PAN. They use the private address to communicate with hosts in the global network. The address/port translation function of PGWs makes proper packet routing between the PAN and the global network possible.

Third, the change of network location of PAN devices when a handoff occurs is concealed through the use of the address/port translation and the session information binding update in PGWs and corresponding hosts. PGWs in a PAN share session information between each other. When a handoff occurs, PGWs will notify the corresponding hosts about the new session information. The PGW and the cor-

responding host will use the session information to perform address/port translation for the session such that the change of network location due to the handoff will be transparent to local devices and application layer of the corresponding hosts. Through the use of session information in the binding update and packet forwarding, our scheme allows devices in PAN to independently switch each of their communication sessions to the appropriate access link without communication interruption.

The following subsections describe our design in more detail.

2.3 Access Link Selection

We designed access link selection management in a distributed manner. Each PGW itself collects the necessary information and selects an access link for each communication session passing through its access links. Our design increases fault tolerance within the highly dynamic environment caused by changes in a PAN's access link resources. In particular, the disconnection of a PGW from PAN due to, for example, a user's movement or battery exhaustion will not influence the services provided by other PGWs.

PGWs cooperate with each other to collect information on all access links in PAN. Each PGW has information regarding its own access link. PGWs exchange the information by sending notification messages to each other. Access link information includes physical information such as link type, up/down status, physical bit rate and information about Internet access service such as per-packet transmission cost.

To detect the change of its own access links' up/down status, each PGW observes the up/down status of its own access links periodically. It will broadcast a notification message immediately after detecting a status change. The notification helps other PGWs to quickly update information of the change on the access link resource information they keep. If a PGW is disconnected from the PAN, the disconnected PGW cannot send a notification message about the disconnection to other PGWs. In this case, other PGWs detect the disconnection of the PGW by link layer information or by the absence of messages that are periodically sent from the PGW.

User preferences are reflected by an access link selection policy. This policy is shared among PGWs in a PAN. Users configure the policy manually via a user interface at each PGW. A newly joining PGW will receive the policy from other PGWs in the PAN. When a user modifies the access link selection policy on a PGW, the PGW will notify other PGWs about the change.

The information set of a communication session includes address/port pairs of a PAN device, translated address/port pairs, address/port pairs of a corresponding host and the type of transport protocol used for address/port translation function. A PGW obtains the information set of a communication session when it performs address/port translation for packets of the session. To cope with their disconnection from the PAN, PGWs periodically backup the

information set of sessions passing through them with other PGWs. They send a session information notification message whenever the information set of a session is created or modified. PGWs use this backup information to perform access link handoffs in the event that a PGW is disconnected from the PAN.

Based on the information it collects, PGWs select appropriate access links for every communication session. If a change of access link resources occurs, PGWs will reselect access links and trigger access link handoff when necessary.

2.4 PAN Mobility Support

PAN mobility support is performed in the PAN area and the global network area for each communication session. In the PAN area, a handoff is triggered by each PGW. When an access link up/down status change occurs, a PGW reselects the access links for all communication sessions passing through its access links. If the access link selected for a communication session is different from the current access link, the PGW will trigger an access link handoff or a vertical handoff for that communication session. It also triggers a horizontal handoff if it detects a change of its attachment point to the access network.

If a PGW is disconnected from the PAN, one PGW in the PAN will instead trigger an access link handoff for the communication sessions of the disconnected PGW. The selection of the PGW that handles packets for each session is done in a distributed manner. When a PGW in the PAN detects the disconnection of another PGW, it will examine the backup information to determine if its access link is the appropriate one for any session passing through the disconnected PGW. If it is, the PGW will use the backup information to perform an access link handoff process for the session.

When an access link handoff of a session occurs, the PGW that handles packets for the session will send a gateway change request message to the PAN device that owns the session. The PAN device will forward packets of the session to the PGW. However, if the PGW, say PGW-1, finds that the PAN device has another session with the same correspondent host and the PAN device forwards its packets to a PGW that handled that session, say PGW-2, it will send a gateway change request message to PGW-2 instead of the PAN device. The PGW-2 will forward packets of the session to the PGW-1 based on session information.

In the global network area, since the address/port of a PAN device is translated to global address/port on the PGW that forwards packets for the PAN device, a horizontal handoff, a vertical handoff or an access link handoff will cause a change of translated address/port. Our PAN mobility support scheme relies on the use of address/port translation and session information binding update at PGWs and corresponding hosts to ensure that PAN device packets are routed and identified properly when a handoff occurs.

Concretely, when a handoff occurs and the translated address/port associated with a communication session is changed, the PGW that handles packets for the session will update the information set of the session on the new translated address/port. The information update allows the PGWs to perform the address/port translation for the session properly. The PGW also update the new translated address/port directly to the corresponding host by a session information binding update message. The corresponding host will perform the address/port translation between old translated address/port and new translated address/port such that packets of the session sent by its application layer will be delivered to new translated address/port and the translated address/port change will be transparent to its application layer.

Our PAN mobility support scheme fits with our flexible access concept because it allows all communication sessions of PAN devices to connect to the Internet via the appropriate access link. When several communication sessions of a PAN device are created simultaneously (e.g. video session, audio session and data session), our scheme can perform access link handoffs for each communication session in order to meet their requirement. Furthermore, since our scheme moves mobility support function to the end host, it does not rely upon any network infrastructure in the Internet for packet forwarding. Therefore, the access link handoff can be done freely with various kinds of access link resources.

3. Implementation

According to the design of Personal Mesh described above, we have implemented a prototype of Personal Mesh. This section describes the detail of our system.

3.1 System Components

We design PGW's communication module with components shown in Fig. 3.

The components of a PGW include:

- Access Link Manager: deals with access link resource information.
- Session Manager: deals with information sets of sessions.
- Access Link Selection Manager: selects appropriate access link and triggers handoff when necessary.
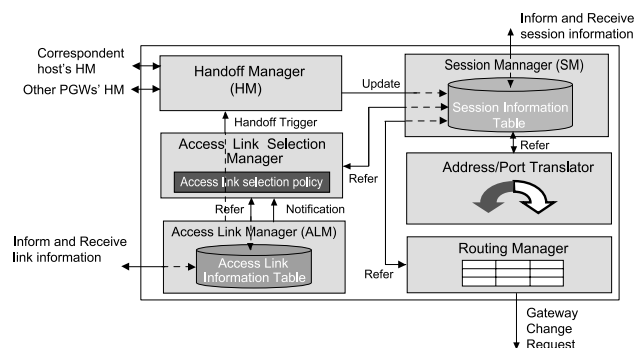

Fig. 3 Structure of Personal Gateway.

- Handoff Manager: exchanges messages with other PGWs and corresponding hosts to realizes seamless horizontal handoff, vertical handoff and access link handoff.
- Address/Port Translation: intercepts packets at network layer, modifies packet header and then sends the modified packets back to the network layer.
- Routing Manager: deals with routing information, modifies its own routing table and send a gateway change request message to a local device or another PGW when necessary.

Corresponding hosts should have at least a Handoff Manager, Session Manager and Address/Port Translation module.

3.2 Access Link Information Management

Access Link Manager handles access link resource information in a PAN and provides this information to Access Link Selection Manager for the selection of appropriate access links.

Access Link Manager receives information regarding its own access links from the operating system, including access link's type, physical bit rate and up/down status. It detects the changes of up/down status and physical bit rate in its own access links by periodically receiving status information. In this paper we do not consider the use of some wireless link information such as bit error rate or signal strength, which changes frequently in poor radio conditions. We leave this for future work.

The Access Link Manager uses notification messages to notify others PGWs about its own access links. The format of the message is shown in Fig. 4a). When a PGW joins a PAN, its Access Link Manager will broadcast a notification message about its access links to the PAN. Other PGWs will send back notification messages about their own access links to the new PGW. The Access Link Manager tracks access link resource information in the PAN in its Access Link Information Table. If the Access Link Manager detects a change in up/down status of its own access links, it will send a notification message to all PGWs in the PAN. By updating Access Link Information Table in a timely manner, access link resource information is kept fresh.

Access Link Manager broadcasts periodic messages (Fig. 4b)) and relies upon the absence of these periodical messages to detect disconnection of another PGW. The message has a lifetime field specifying the period of time during which the PGW are considered to be available. Periodical messages may be lost due to bad link conditions. Hence, when the lifetime of a PGW has expired, the Access Link Manager will query the PGW several times within a specified period called known as a guard time before considering the PGW to be disconnected. To reduce the network overhead related to periodic message transmission, the Access Link Manager will increase the broadcasting period when there is no communication session passing through its own access links.

When the Access Link Manager detects a change of up/down status in its own access links, detects the disconnection of a PGW, or receives a message about the change of an access link from another PGW, the Access Link Manager will update the Access Link Information Table and notify the Access Link Selection Manager about the change. It receives a new global address and sends a horizontal handoff trigger to the Handoff Manager when detecting a change of its access link's attachment point to the access network.

3.3 Access Link Selection and Handoff Trigger

To select an appropriate access link for each communication session, the Access Link Selection Manager first receives the information set of the session from the Session Manager. Based on session information such as the source port or destination port, it will determine the type of application that owns the session. It then receives information on each access link from the Access Link Manager and calculates the priority of each access link based on Access link selection policy. The access link that has highest priority is selected. A priority calculation method such as that presented in [11] can be applied to our framework.

When the Access Link Selection Manager receives notification about the change in up/down status of access links in the PAN from the Access Link Manager, it asks the Session Manager for information sets of all communication sessions passing through it and reselects the access link for each session. If it finds the selected access link for a session is the access link of another PGW, it will send an access link handoff trigger to the Handoff Manager. If it finds that the selected access link is another access link of it, it will send a vertical handoff trigger to the Handoff Manager.

The Access Link Selection Manager also selects an access link after a communication session is established. A local device uses the default PGW to establish a communication session. When the Session Manager finds that the session is established, it will ask the Access Link Selection Manager to select an access link for the session. If the selected access link belongs to another PGW, it will trigger an access link handoff to the Handoff Manager. Here, the default PGW is selected among PGWs in the PAN by the
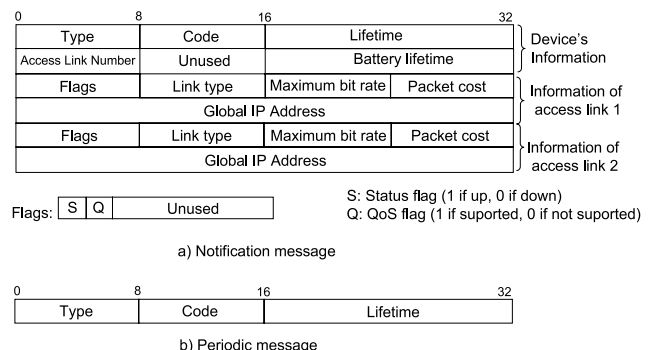

Fig. 4 Format of access link information notification message.

Access link selection policy and the local device receives information regarding the default PGW when it joins PAN. If the default PGW is disconnected from the PAN, another PGW will be selected and local devices will change their default PGW.

When the Access Link Selection Manager receives a notification about the disconnection of a PGW, it receives the information set of all communication sessions passing through the disconnected PGW and then reselects an access link for each session. If it finds the selected access link is its own, it will send an access link handoff trigger to the Handoff Manager.

3.4 Session Management

The Session Manager keeps information sets of all communication sessions of all PAN devices in the Session Information Table. Whenever the Address/Port Translator receives a packet from the network layer, it will give the address/port pairs of the sender and receiver, and the type of transport protocol to the Session Manager. The Session Manager will use the Session Information Table to find the information set of the session that the packet belongs to and give the information set to the Address/Port Translator. If the information set does not exit, the Session Manager will create a new one. Each time the information set of a communication session is created or changed, the Session Manager will send a notification message containing the new information set to other PGWs. Other PGWs will keep the information in the Session Information Table to use when an access link handoff occurs or when a PGW is disconnected from the PAN.

The address/port translation mechanism on PGWs and corresponding hosts allows local devices in the PAN and application layer of corresponding hosts to be unaware of the change of session information. Figure 5 shows the communication session between two local devices A and B of two PANs and shows how address/port translation is made to maintain a communication session between A and B after an access link handoff. After an access link handoff of the session from PGW-A1 to PGW-A2, the translated address/port used for the session is changed from $IP_{PGW-A1}/Port_{PGW-A1}$ to $IP_{PGW-A2}/Port_{PGW-A2}$. PGW-A2 will update PGW-B on the new address/port pairs $IP_{PGW-A2}/Port_{PGW-A2}$. The Session Manager of PGW-B will use $IP_{PGW-A1}/Port_{PGW-A1}$ to identify packets sent by local device B and to translate packets delivered to local device B, and use $IP_{PGW-A2}/Port_{PGW-A2}$ to identify packets sent by local device A and to translate packets sent to local device A. Hence, both local devices A and B can send and receive packets with unmodified packet header (Fig. 5). In the case of a horizontal or vertical handoff, address/port translation is done similarly.

The global address of a PGW may change dynamically and private addresses are only meaningful within a PAN. To allow an Internet host to initiate communication with a device in a PAN, a naming system that can dynamically update the global address of PGWs such as dynamic DNS or SIP can be used. Each user may have a domain name that matches to one or several global PGW addresses. Furthermore, a device in a PAN that opens a port for Internet hosts can register the port with the PGWs' Session Manager. If an Internet host sends a packet to the registered port to initiate communication, the Session Manager will use address/port of the PAN device to create a new information set of the session and perform address/port translation for packets of the session. To implement the registration function, a program installed in local devices observes the socket system call to get opened port number and registers the port number with PGWs

Our mobility support scheme requires correspondent hosts to implement address translation function and address/port binding update function to maintain communication sessions. However, from practical point of view, there are CHs that have no PGW function. If a correspondent host does not implement PGW software module, PGWs can rely on a proxy that implements PGW functions to maintain the communication session. In this case, the address of the proxy will be given to the correspondent host by default to initiate the communication session.

3.5 Handoff Management

We have implemented a protocol for the Handoff Manager to ensure that new translated address/port pairs will be updated to PGWs and corresponding hosts whenever an access link handoff, a vertical handoff, or a horizontal handoff occurs.

Figure 6 shows how our protocols works in the case PGW-A2's access link comes up and the communication session between A and B is switched to route through the access link of PGW-A2 instead of the access link of PGW-A1 (Fig. 5). PGW-A1's Handoff Manager sends an access link handoff request message to PGW-A2 after it receives a trigger from its Access Link Selection Manager. The access
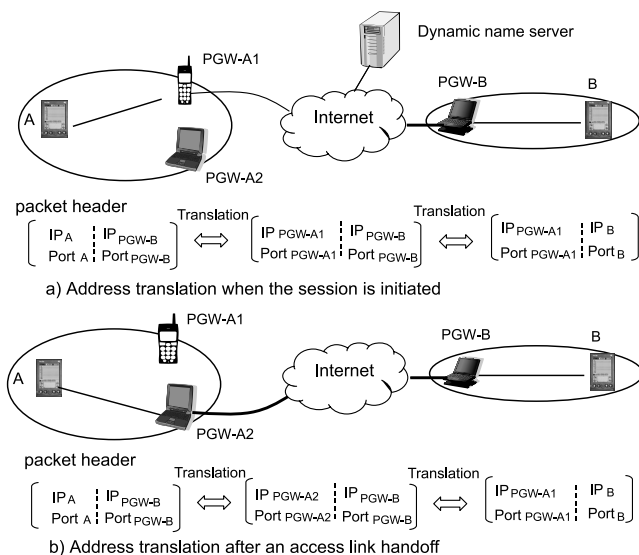

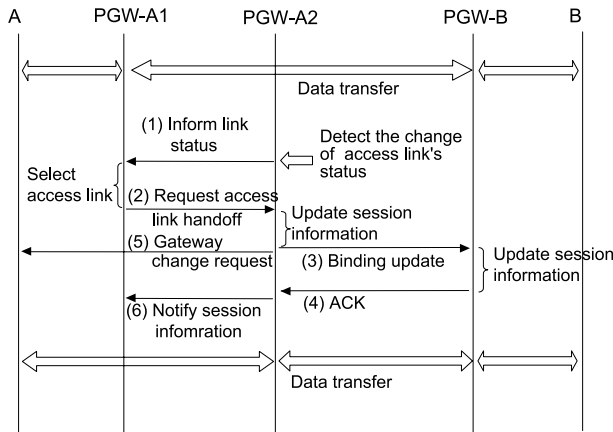**Fig. 5**   Address/port translation based on session information.

Fig. 6 Access link handoff in PAN.

Fig. 7 Format of binding update message.

link handoff request message contains information set of the session between A and B. After receiving the request message from PGW-A1, PGW-A2's Handoff Manager updates the Session Manager on the new translated address/port of the session and sends a binding update message (Fig. 7) to the corresponding host PGW-B. The Session Manager then triggers the Routing Manager to send a gateway change request message to local device A. After the Handoff Manager receives ACK message from PGW-B, it triggers the Session Manager to send a notification message about the new information set of the session to PGW-A1. Consequently all PGWs in the PAN and the corresponding host PGW-B can update their Session Information Table with the new session information and perform the address/port translation properly. To identify on-the-fly packets that are sent by the corresponding host before the handoff finishes, PGW-A1 performs the address/port translation temporally until it receives the notification message from PGW-A2.

Note that before triggering the Routing Manager, PGW-A2's Session Manager will lookup the Session Information Table to determine if there is another communication session between local device A and PGW-B (A is considered to communicate with PGW-B). If there is and PGW-A1, for example, handles that session, PGW-A2's Session Manager will trigger the Routing Manager to send a gateway change request message to PGW-A1 instead of local device A. PGW-A1's Routing Manager will set a routing policy that allows session packets handled by PGW-A2 to be forwarded to PGW-A2.

In the case PGW-A1 is disconnected from the PAN and PGW-A2 considers that its access link is the appropriate access link for local device A, before performing the access link handoff, PGW-A2 will send a notification message to notice other PGWs about the access link handoff.

In the case of a vertical handoff, only a binding update message to the corresponding host and a notification message to other PGWs are sent. The Handoff Manager will send a trigger to its Routing Manager to change the route destined for the corresponding host. In the case of a horizontal handoff, only a binding update message is send to the corresponding host.

4. Experiment and Evaluation

We have implemented the prototype of Personal Mesh on our testbed network. We confirm the operation of our system through four experiment scenarios: vertical handoff, access link handoff when a new access link comes up, access link handoff when an access link goes down and access link handoff when a PGW is disconnected. We also evaluate our implementation system's performance by measuring the handoff time on the above experiments and investigate the influence of system parameters on the handoff time.

This section shows the details of our experiment.

4.1 Testbed Network

In our testbed network, PAN is constructed from a PDA running Melon Linux as a local device and two laptops running FreeBSD-4.7R as PGWs (Fig. 8). Laptop (a) has IEEE 802.11b wireless LAN and IEEE 802.3 Ethernet LAN cards functioning as access links, and Laptop (b) has an Ethernet LAN access link. Each device has another IEEE 802.11b wireless link operating in ad-hoc mode to form a PAN. Packet transmission delay between devices in the PAN is 1.1 ms. The corresponding PC runs FreeBSD-4.7R. The router PC fixes the delay between two laptops and the corresponding PC at 10 ms. The bandwidth of access links (1), (2) and (3) are 10 Mbps, 10 Mbps and 2 Mbps respectively.

The FreeBSD divert socket is used to intercept the packets passing through network interface for packet header modification. To forward packets from a PGW to another PGW based on session information, the packet forwarding function of the FreeBSD firewall is used. The up/down status of an access link is observed periodically with the period fixed at 20 ms. PGWs advertise their access link information periodically with an interval of 200 ms.

We confirmed the operation of our prototype with following four experiments on our testbed network.
(1) When the PDA communicates via the wireless LAN of Laptop (a), plugging the Laptop (a)'s Ethernet LAN cable into the hub (the Ethernet LAN came up). Experiment result: the PDA's communication session is switched to the Ethernet LAN (i.e. a vertical handoff).
(2) When the PDA communicates via the wireless LAN of the Laptop (a), plugging Ethernet LAN cable of the Note-
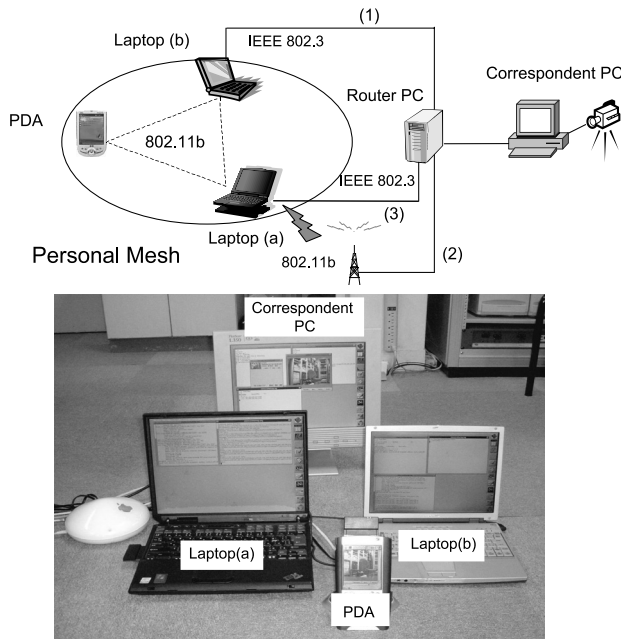
Fig. 8   Testbed network.

Table 1   The handoff time in four experiment scenarios.

	Exp(1)	Exp(2)	Exp(3)	Exp(4)
Detect access link resource change (Td+Tn+Tdp)	≤ 20.0 ms	≤ 21.1 ms	≤ 20.0 ms	≤250 ms
Select access link (Ts)	0.3 ms	0.3 ms	0.3 ms	0.3 ms
Request access link handoff (Ta)	0 ms	1.1 ms	1.1 ms	0 ms
Send binding update (Tb)	10 ms	10 ms	10 ms	10 ms
Total handoff time (Th)	≤ 31 ms	≤ 33 ms	≤ 32 ms	≤261 ms

book (b) into the hub (Laptop (b)'s Ethernet LAN came up). Experiment result: the PDA's communication session is switched to the Laptop (b)'s Ethernet LAN (i.e. access link handoff when a new access link comes up).
(3) When the PDA communicates via the Ethernet LAN of Laptop (b), pulling the Laptop (b)'s Ethernet LAN cable out of the hub (the Ethernet LAN went down). Experiment result: the PDA's communication session is switched to the Laptop (a)'s wireless LAN (i.e. an access link handoff when an access link goes down).
(4) When the PDA communicates via the Ethernet LAN of Laptop (b), Laptop (b) is disconnected from the PAN. Experiment result: the PDA's communication session is switched to the Laptop (a)'s wireless LAN (i.e. an access link handoff when a PGW is disconnected).
The applications running on PDA and the corresponding PC are FTP and VIC [21].

4.2   Evaluation

We evaluate the performance of our implemented system by measuring the handoff time on the above experiment scenarios. The handoff time is measured from the time the access link status changes until the time the update of session information on PGWs and correspondent hosts is finished. If an access link becomes down, a PGW is disconnected from PAN, or a PGW changes its point of attachment to the access network, the communication session will be temporarily disconnected until the handoff is finished and on-the-fly packets will be lost. Hence, the handoff time is an essential parameter to evaluate the viability of our system. We also plot sequence number of TCP packets versus packet arrival time when a handoff occurs in order to clarify the influence of the handoff time on TCP connections.

The handoff includes following elements: the time to detect the change of access link up/down status (Td), the time to detect the disconnection of a PGW (Tdp), the time to receive a notification of a change of access link status (Tn), the time required to select access links (Ts), the time required to transmit access link handoff request message (Ta) and the time required to send a binding update message (Tb). However, the total handoff time does not include all these time elements. In each above experiment scenario the total handoff time (Th) is as follows.

(1) Vertical handoff: Th = Td + Ts + Tb. Because the PGWs themselves perform the vertical handoff, the time to receive a notification of a change of access link status (Tn) and the time required to transmit access link handoff request message (Ta) are 0.
(2) Access link handoff when a new access link comes up: Th = Td + Tn + Ts + Ta + Tb
(3) Access link handoff when an access link goes down: Th = Td + Ts + Ta +Tb. Because the PGWs themselves detect the change in status of its access link, the time to receive a notification of a change of access link status is 0.
(4) Access link handoff when a PGW is disconnected: Th = Tdp + Ts + Tb. Because the PGWs themselves detect the disconnection of another PGW and perform the binding update, the time to receive a notification of a change of access link status (Tn) and the time required to transmit access link handoff request message (Ta) are 0.

Table 1 shows the handoff time in the four experiment scenarios. Here, we call the sum of the time to detect the change of access link status (Td), the time to detect the disconnection of a PGW (Tdp), and the time to receive a notification of a change of access link status (Tn) as the time required to detect the change of access link resources. Since access link up/down status is observed periodically with the period fixed at 20 ms, the time to detect the change of access link status (Td) is less than 20 ms. The time to receive a notification of a change of access link status (Tn) is the transmission delay in PAN or 1.1 ms. The time required to detect a disconnection of a PGW (Tdp) in the worst case is 250 ms. It is because the interval to send a periodic message is set to 200 ms and the guard time is set to 50 ms. The time required to select access links (Ts) is measured by experiment and is about 0.3 ms. The time required to transmit
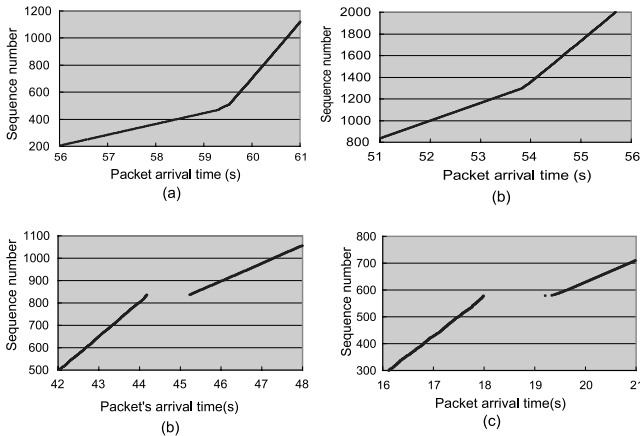
Fig. 9 TCP packet's sequence number when of access link handoff.

access link handoff request message (Ta) is the transmission delay in PAN or 1.1 ms. The time required to send a binding update message (Tb) to the corresponding PC is the transmission delay between the PGWs and the corresponding PC, or 10 ms. The total handoff time in each experiment is measured by sending 1 UDP packet/ms from the corresponding PC to PDA and plotting down the arrival time of these packets.

Our results show that the time required to transmit access link handoff request message and the time required to select access links is relatively small compared to the amount of the time required to send a binding update message and the time required to detect the change of access link resources in the PAN. To improve handoff performance, we must reduce the amount of time required to detect access link resource changes. This issue will be the focus on future work.

Figure 9 plots the sequence numbers of the received TCP packets of the file download application versus time for each experiment.

In experiment (1) and (2), packets were transmitted continuously during the handoff because on-the-fly packets were handled by the previous PGW and the corresponding PC until the handoff finished. In experiment (3) (4), the communication session was disconnected for a period time of about 1 second. The disconnected time was longer than the handoff time because TCP sockets did not send packets until the TCP connection timeout expired.

5. Related Works

Communication environment allowing a user to access multiple devices has attracted the attention of many researchers. The Always Best Connected (ABC) concept given in [14] considers a network model in which personal devices, network access operators and service providers cooperate with each other to provide the best suited access service to users. Although the concept of ABC is similar to our Personal Mesh's concept, technical issues such as access link selection management and seamless access link handoff are left open in the paper.

In [15], an adaptive terminal middleware (AMID) was proposed to allow a mobile phone to control the communication sessions of a network application and assign these sessions to surrounding devices dynamically and adaptively. Although AMID local devices can use the Internet access links of the mobile phone, it does not allow local devices to use the Internet access links of other devices. Hence, failure of the mobile phone due to physical damage or battery power drain will cause the failure of a local device's communication even though there may be an available access link in other surrounding devices.

A PAN with multiple access links can be considered as a multi-homed network. Multi-homing technologies are now considered to enhance the reliability and the performance of network connectivity [16]–[19]. Since the target of these researches is on multi-homed wired networks, only the change of access link status is considered and local devices within multi-homed wired networks must cope with the change of access link status. However, in the case of PANs, the change in the point of attachment to the access network and the arrivals/departures of PGWs due to user movement must be also considered carefully. Furthermore, there are functionally limited local devices which can not cope with the change of access link resources. Hence, PGWs must support the change for these devices. These issues are dealt with in our work.

VNAT [4] utilizes address/port translation to maintain communication of mobile hosts when mobile hosts migrate to a new physical endpoint. Our approach is similar to this approach in the use of address/port translation at both end hosts to maintain communication. However, while the scope of VNAT is to support mobility of a mobile host, our work realizes the mobility support issue for a PAN. Hence, several technical problems that are not considered in VNAT such as mobility transparency for local devices, access link selection or access link handoff are dealt within our works.

The IETF NEMO working group have discussed a mobility support protocol for mobile networks like a PAN by a bi-directional tunnel between a Home Agent (HA) and a mobile router (i.e. a PGW) [9], [20]. However, the basic NEMO protocol has not considered about the access link handoff and the selection of an appropriate access link for each communication session. As described in Sect. 2.2, with the concept of the basic NEMO design that is to handle packet routing at network layer, HAs can not identify packets of different communication sessions destined to a device in PAN and therefore can not forward the packets to different access links at the same time. Therefore, a device in PAN can not select different access links for its communication sessions. Furthermore, if mobile routers are associated with separated HAs, it is difficult to maintain communication when a mobile router is disconnected from PAN.

MOPED [10] uses a private address space for a network of mobile devices to present them as a single entity in the Internet. MOPED relies on a Home Agent located on the global network to send and receive packets to and from

the network and uses a hierarchical packet capsulation for proper packet routing. MOPED's design is different from our concept in that it requires local devices in a PAN to encapsulate packet and to select access links by themselves. Therefore, local devices must have several extra-functions implemented. This requirement is contrary to our design's concept.

6. Conclusions

In this paper, we presented the design and implementation of Personal Mesh, a framework which allows devices in PAN to seamlessly use the appropriate access link in the PAN to access to the Internet. Our framework copes with the dynamic change of access link resources through the cooperation between PGWs and between PGWs and corresponding hosts.

We described a flexible access link selection management which enables PGWs to select appropriate access links for every communication session of devices in PAN. A PAN mobility support scheme realized by a session information binding update scheme and an address/port translation function at PGWs and corresponding hosts was also presented. The scheme allows PAN devices to freely switch each communication session to an appropriate access link without communication interruption.

We have confirmed the operation and evaluated the performance of our Personal Mesh system on a test-bed network. Our experiment proved that the time to exchange messages between PGWs and the time to select an access link was fairly small compared with total handoff time. The handoff time can be reduced greatly by reducing the amount of time required to detect access link resource changes.

Our future work is directed towards securing our protocol. Although negotiations between PGWs and between PGWs and corresponding hosts can become the target of attacks, we believe that existing security architectures [22], [23] can be applied to our protocol thereby increasing security.

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