PUCS: Personal Unified Communications over Heterogeneous Wireless Networks

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***Abstract*—Communication systems are becoming more complicated to support different types of services. How to coordinate different services around a user in a flexible and customized way is a new and interesting challenge. Service providers have proposed solutions such as the Universal Communication Identifier (UCI) and IP multimedia subsystem (IMS) but they require the modification of current systems and only perform the service integration in their service domains. On the other hand, unified communications (UC) solutions have been proposed to support service integration across different service domains. In this paper, we proposed a personal unified communication system (PUCS). This system uses personal-oriented modules which allow it to integrate any communication services over heterogeneous wireless networks around a user in a customized and flexible way. Users can then enjoy unified communications in their personal domains without support from public or group service providers. The PUCS can provide users with UC capabilities such as personal mobility (PM), any-to-any communications, user presence, instant message (IM), unified messaging, speech access, and text access. The solution is scalable since it is implemented on personal domains. A further advantage is that, by using a universal personal identifier (UPI) and an alias system, a user can also be affiliated with different group domains. This makes it possible to define specific service profiles for each domain so that the user can also enjoy the unified communications provided specifically for that domain.**

I. Introduction

One of the ultimate goals of future communication systems is to enable users to communicate with each others any time, any place and in any form. Over the last two decades, many researchers have tried to achieve this in wireless networks by providing users with ubiquitous communication capabilities that complement to traditional communications services. In addition to mobile communication systems (MCSs) that provide users with basic telephony services while supporting terminal mobility, we have seen more and more communication services emerging on the Internet, such as voice over IP (VoIP) and instant messaging (IM). Users can easily access these services via wireless IP networks using IP-based terminals such as laptop computers, personal digital assistants and smart phones. Recently, there has been considerable interest in integrating all of these services over all access networks so as to provide users with a unified communication (UC) environment. For example, the next generation (NG) MCSs aim to provide various communication services through an all IP-based system [1] where users can access the services via heterogeneous wireless networks. The major issue with such an NG system, however, is that users nowadays commonly employ multiple terminals to access different communication services via different wireless access networks, making it a real challenge to provide converged services to users in a flexible, customized and intelligent way.

There have been many studies on the integration of different wireless communication services for users over the last decade. Most of these studies have focused on how to provide users with personal mobility (PM) [2][3], i.e., the ability for users to use different terminals and subscribe to different services while enabling other users to communicate with them using just one identifier. A number of schemes have been proposed [4][5] to implement PM in MCSs using Universal Personal Telecommunication (UPT) as defined by ITU-T [6]. The drawback of UPT is that while it focuses on the integration of telephony services by providing a unified telephony service across different countries (i.e., a single telephone number that can be used in different countries), it does not support IP-based services like VoIP and IM.

Another reason to study how traditional telephony services can be integrated with IP-based communication services is the fact that in Universal Mobile Telecommunication Service (UMTS) release 5 from the 3rd Generation Partnership Project (3GPP), the core network of the third generation (3G) MCSs becomes entirely IP-based. To achieve such a goal, the Internet Engineering Task Force (IETF) has proposed the E.164 NUmber Mapping (ENUM) protocol [7][8] which maps an E.164 telephone number into a Uniform Resource Locator (URL). This mapping can be used to query a specific Domain Name System (DNS) server, which in turn allows the URL to be translated into a Naming Authority Pointer Record (NAPTR). The caller then uses this NAPTR to determine the protocol to be used for the call and to identify the terminal address of the callee. The advantages of this are that it allows first, a traditional telephone number to be translated into an IP-based communication service address and second, traditional telephony services to be integrated with other IP-based communication services.

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3GPP has specified the IP multimedia subsystem (IMS), which functions as an overlay signalling network over the packet-switched transport networks [9]. IMS is intended to support MCSs on the Internet so that subscribers can enjoy more services on the Internet [10]. With IMS, all telecommunication services provided by different interworking IMS networks can be integrated as one for users, who can access these services from any of these IMS networks. A further benefit is that IMS provides service interfaces that allow users to access third party services offered by their IMS service providers. Certain modifications on existing MCSs are required to utilize IMS services.

An improvement to UPT, the Universal Communications Identifier (UCI) [11][12][13], has been proposed by the European Telecommunications Standards Institute (ETSI). UCI will make it possible to provide users with logical global identities that they can use to communicate over any service network without changing their identities. The use of UCI means that different services can be integrated as one global service, providing users with universal communication capabilities. The implementation of UCI is not a simple matter: first, it requires modifications in all involved service networks; second, if UCI is to be globally available and compatible with any service type, these modifications must be implemented in every single service domain in the world. One particular advantage of UCI is that it is an abstract model, so that it can be implemented in different service networks using different technologies. A good example of this is the possible incorporation of the UCI and ETSI TISPAN (Telecommunications and Internet converged Services and Protocols for Advanced Networking) in [14]. While it will be difficult to implement UCI globally in all service networks, on the whole, UCI can effectively provide users with PM while being compatible with both traditional telephony services and IP-based communication services.

A number of approaches have been proposed to integrate services in heterogeneous wireless environments. ENUM only provides the address and communication translations from telephony services to IP-based services but not in the reversed direction. Also, such translations occur over the public domain (the DNS server) so that privacy and security can become a serious problem. IMS provides service integration among all service networks and also third-party services. However, it requires the modification of all service networks and cooperation between different service providers. UCI provides an abstract model to implement service integration. However, its implementations in different service networks are not yet widely available. It will be difficult to support UCI globally in all service networks.

In this paper, we proposed a Personal Unified Communication System (PUCS) that will provide service integration in the personal domain for different services accessible via wireless and wireline networks. This service integration does not require the modification and co-operation between service networks because the service interfaces are implemented in the personal domain (personally operated), allowing the effective integration of different services in a global manner. PUCS also provides users with a UC [15] solution. The proposed PUCS takes the novel approach of focusing on integrating all services around an individual, which is very different from most current UC solutions that are designed to support a user group, e.g., a corporate work group. Our approach allows users to use UCs with personal-oriented modules whether or not peer communicating nodes are using the same system, which makes PUCS very much scalable. Furthermore, besides providing UCs on personal domains, PUCS also enables group-based UC by employing third-party modules. By doing so, a user can have personal UC services in his/her personal domain that integrates with one or more group UCs services in different group domains.

The rest of the paper is organized as follows. Section II discusses related work on service integration and UC. Section III presents the proposed PUCS. Section IV evaluates the PUCS and Section V concludes the paper.

II. Related Work

A. E.164 NUmber Mapping

The ENUM protocol, proposed by ETSI, allows an E.164 number to be mapped to other types of addresses and informs the caller or caller's agent which protocol should be used for that address. Most often, VoIP service providers use it to bypass the access to the Public Switched Telephone Network (PSTN), thereby reducing costs [16].

The VoIP system permits terminal-to-terminal voice communications using the Session Initiation Protocol (SIP) [17][18]. Under this system, an SIP address is assigned to each VoIP terminal. An E.164 telephone number is also assigned to each VoIP terminal to support PSTN calls. When an incoming call from PSTN arrives at the gateway of the VoIP system, it is turned into an SIP call. Similarly, when an outgoing SIP call arrives at the gateway, it is turned into a PSTN call.

In this approach, the traffic needs to pass through the PSTN network when a call is made between two different VoIP service domains with a telephone number as the dialling address. However, if the two service providers can cooperate with each other, this step can be bypassed to avoid accessing the PSTN. One way is to store all telephone numbers belonging to one service domain in a database for the other service domain, so that the other service domain can direct the call correctly by checking the database. However, the use of ENUM makes the cooperation much easier.

When a call arrives to the VoIP gateway of a service provider, the destination number is translated into a URL according to the ENUM protocol. The gateway then sends a query to the DNS for that URL and gets the corresponding NAPTR. The returned record may contain different real addresses for the callee's terminals and also information on the different protocols that are used to communicate with these addresses. The VoIP gateway then tries the addresses successively to communicate with the callee. If the VoIP gateway that serves the callee registers the callee's SIP address in the DNS server for the callee's telephone number, the

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caller's gateway will direct the call to the gateway of the callee's service provider by SIP instead of via the PSTN.

B. IP Multimedia Subsystem

The main components of the IMS are the three types of Call Session Control Functions (CSCF): Serving CSCF (S-CSCF); Proxy CSCF (P-CSCF); and Interrogating CSCF (I-CSCF). All IMS networks must implement all three CSCFs. All users must individually register with an IMS network which will become their home IMS domain (or home domain). The home domain contains an S-CSCF that functions as the user's home proxy SIP server, and a Home Subscriber Server (HSS) that stores that user's profile and service information. This S-CSCF supports signalling interactions with the user's terminal which could be in any IMS domain for session setup and supplementary service control. A user of the IMS service may be in any IMS domain (including their home domain). The P-CSCF in the IMS domain where the user is currently located executes limited address translation function and forwards SIP signalling messages between the user's terminal in the current IMS domain and the S-CSCF in the user's home domain. P-CSCF also performs the authorization of bearer resources for the user in the current IMS domain. I-CSCF is the contact point of an IMS domain. Its role is to hide the configuration, capacity, and topology of IMS domains from the external world. Any signalling messages sent to an IMS domain must first be sent to the I-CSCF of the domain. The I-CSCF then uses the information stored in the HSS to determine which S-CSCF the message should be delivered to. IMS provides a logical SIP address to each user. Users who wish to access IMS should first authenticate a terminal in the current domain and then authenticate with the S-CSCF in its home domain with the SIP address. By dynamically binding the SIP address to the terminal currently used by the user, the user can be addressed and identified in any IMS enabled domain. Further, IMS can also support third party services such as voice mailbox services by providing interfaces behind the S-CSCF.

C. Universal Communication Identifier

UCI requires every communication service provider to implement a Service Agent (SA) in its own network as an interface with the UCI system. It also requires each user in the UCI system, before using a terminal, to register the terminal with a Personal User Agent (PUA) via the SA of the service network. The UCI system provides address mapping between the global personal identifiers and real addresses of terminals in a specific service domain. To make a call, the caller should first send the request to his/her PUA via the SA of his/her current service network through his/her current terminal. Then the PUA sends the request to the callee's PUA and the two PUAs negotiate how to make the connection. The caller's PUA then informs the SA of the caller's current service network and a communication instance is established between the caller's current terminal and the callee's preferred terminal (as determined by the callee's PUA) [13]. The UCI system provides PM among its service domains. These services can be traditional telephony services, VoIP services, IM services, and so on.

D. Unified Communications

There are a number of definitions of UC. UCStrategies.com has defined UC as "communications integrated to optimize business processes". However, the definition of UC is sometimes expanded to encompass the next generation of IP communications. According to [15], UC is a solution for managing various types of communications service across geographical boundaries and networks according to certain personalized rules and policies. It improves overall user service experience by providing seamless integration between different services [15]. UC should include components for call control and multimodal communications, presence, instant messaging, unified messaging, speech access and personal assistant, conferencing – audio, web and video, collaboration tools, mobility, business process integration (BPI) [15]. In this paper, we treat UC as a more general service integration which provides users with a better communication experience.

There have been different mechanisms proposed for UC. The "Universal Inbox" [19] provides PM over heterogeneous networks and the capability of any-to-any communications. In [20][21], a new system called "ICEBERG" is proposed to realize UC, which includes any-to-any communications, PM, communication service customization, user activity-driven services and multi-endpoint communications. A context-aware UC system called "Mercury" [22] integrates services not only in the initial routing phase but also during the communication period. A system called "BKUMN" [23] provides UC for a campus environment based on the peer-to-peer SIP protocol. Recently, many business UC solutions have been marketed. For example, Ayaya, Cisco, Siemens, Microsoft and Siemens all have their own desktop UC solutions on the market.

Previously proposed solutions for UC have normally been implemented in a group domain such as a business corporation or an organization. They have focused on the service integration for users in the group, specifically for communications among users in a group domain. Take for example the Mercury system [22]. The Mercury system has an extensible set of device agents, a Mercury Engine and the context service. Device agents are used as access points for different types of communication devices and to manage sessions involving these devices. The Mercury Engine looks up addresses via an address book, makes decisions on communication session setup, and supports routing functions. Mercury uses SIP as the underlying protocol for creating, maintaining and terminating communication sessions. The Mercury Engine acts also as a SIP server and Device Agents act as SIP terminals. The Mercury system can provide call control, multimodal communications, presence, IM, and unified messaging.

III. Proposed PUCS

In this section, we provide a more detailed description of PUCS, which integrates different services over heterogeneous wireless (and wireline) networks. The major components of the

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PUCS are the personal proxy server (PPS) and the personal gateways (PGs). Fig. 1 shows the global view of the PUCS. A user may own several terminals. However, all these terminals can be registered to the PPS via the service interfaces implemented in PGs. This allows all of these terminals to compose a logical global personal domain and enables users to access integrated services from any of the registered terminals.

A crucial feature of PUCS is that it allows a user to be reached through an operator-independent universal personal identifier (UPI), no matter how many terminals he/she has, which terminal(s) he/she is using and what kind of service(s) he/she is subscribing to. PUCS also provides the mapping from any terminal address of any user to his/her UPI. This means that a call to a user's terminal can be answered using any of the user's other terminals. To ensure privacy and security, the mapping between the UPI and terminal addresses is stored in the personal domain and is not disclosed to the public. PUCS achieves communication control by using the presence information for each terminal. Communication control governs which terminal should be used to answer a specific call (but the user can also define specific policies or priorities which the PUCS uses to make such decisions). Unlike UCI and IMS, where each service network is responsible for publishing or reporting the presence information of all its terminals, PUCS is responsible for tracking the presence information of the user's terminals. In PUCS, when a caller calls one of the user's terminals, the user may choose to receive the call on another terminal. So it is possible for a call to start with one type of communication service from the caller's terminal and reach the user's terminal as another type of communication service. PUCS provides the necessary translation between the two types of communication services and sets up cascade calls of the appropriate type to support the communication session.

This kind of any-to-any communication function is another important feature provided by PUCS. When the user is not at a terminal or do not want to answer a communication request right away, the communication request can be answered by PUCS and a one-way communication session can be setup (such as voice message, email, off-line message, or SMS message and so on). PUCS provides the control of the one-way communication session so that the user can choose to store the received communication message in any pre-determined place. PUCS also provides a command interface that allows the user to use any terminal to access PUCS and to configure the whole system, initialize a UPI-based communication session, access the stored messages, obtain stored personal information, and so on.

A. *Personal Proxy Server*

The PPS acts as a communication control centre of the PUCS and contains several different modules that perform different tasks. The PPS is located on the public Internet with a domain name (URL) (we consider a user *Jack* here and assume *jack.PUCS.com* is used as the URL for his PPS). Fig. 2 shows the architecture of the PPS. The PPS enables the addressing/identifying the user with his/her UPI or alias and provides the communication control for the PUCS so that communication sessions around the user can be intelligently combined.

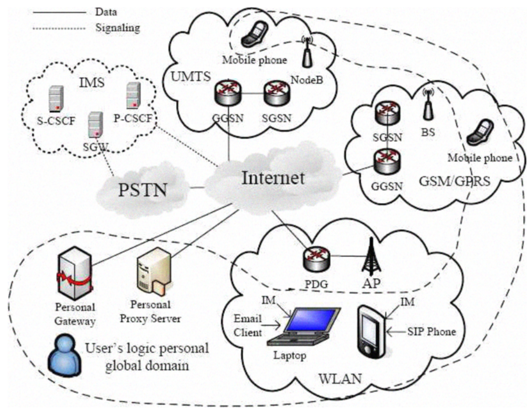

Fig. 1. Global view of the PUCS

1) Signaling module: The signalling module processes signalling messages for the user. The PPS must exchange signalling messages with the user's PGs, other users' PPSs, and possibly third-party services. SIP is employed here to exchange most signalling messages between PPSs. Specific messages are used between PPS and PGs to perform different functions. Third-party services such as ENUM require the provision of compatible signalling protocols. For example, the signalling module may send a query message to a DNS server and receive a NAPTR record according to the ENUM protocol.

2) Web interface: The PPS also provides a web interface module so that the user can easily access configuration and other personal information stored in the PPS.

3) Service coordination module: The service coordination module is the brain of the PPS. It is an intelligent decision system that controls communications for the user. It coordinates with the PGs and other users' PUCS via the signalling module so as to help the user establish communication sessions according to presence information, profiling information, and possible alias destination addresses.

4) Naming system: The naming system manages the UPI defined for the PUCS and aliases. By registering its IP address

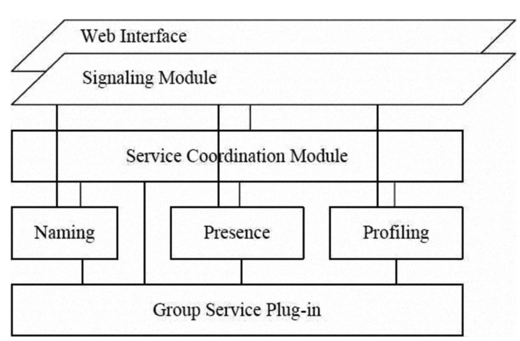

Fig. 2. The personal proxy server

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at the DNS, the PPS can provide a public SIP address for the user (say *main@jack.PUCS.com* for *Jack*) as the user's UPI. Other PUCS can use this address to easily address the user's PUCS. So as long as both peers are using PUCS, they can address each other using UPI.

If a user wishes to publish his/her customized presence information during a communication session, it is possible to define alias addresses for that purpose. For example, *jackisworking@jack.PUCS.com* or *jackathome@jack.PUCS.com* can be provided by the naming system so that *Jack* can specify his presence during a communication session to let other people know something about him immediately. This kind of alias can also be used for other people to address the user only in a specific situation. For example, a friend of *Jack* may only want to call *Jack* if *Jack* is not working so he calls to the address *jackoffwork@jack.PUCS.com*. Note that, when the PPS receives a communication request with an alias as the destination address, the service coordination module checks the profiling system to search for specific profiles according to the alias to determine where and whether the communication request will be accepted.

Another kind of alias can affiliate the user with some group UCs. For example, *Jack* can also be an employee of a company called *PUCS-ABC*. If a specific domain name *jack.PUCS-ABC.com* is defined and also mapped to *Jack*'s PPS, any communication requests to that address *jackisworking@jack.PUCS-ABC.com* will be directed to *Jack*'s PPS. A request can be further processed by the service coordination module with the help of group service plug-in modules.

5) Presence module: The presence module is a database that manages the registration and the presence status for the user. A user may own many terminals with different addresses and perform different actions on each terminal at different times. The presence module stores the address of each terminal, its current status, as well as its communication capacity. For example, at a specific time, the presence module knows that the user is currently busy communicating on his/her mobile phone and also knows the telephone number of the mobile phone. It should also know that this mobile phone can receive SMS and voice messages. When the presence information of one terminal changes, the presence module should update its status. The presence information is obtained by the service interface defined in the PGs or reported via a Web interface defined in the PPS. The service coordinator module will use this information in making decisions on setting up communication sessions.

6) Profiling module: The profiling module uses a database to manage predefined profiles for communications. A profile consists of the user's preferences, scheduling, service charging information, quality of service information, etc., for communication purposes. Users can have multiple profiles since users can have different roles defined in different groups with different communication capabilities and preferences. These profiles will also be used by the service coordinator module in making decision about setting up communication sessions.

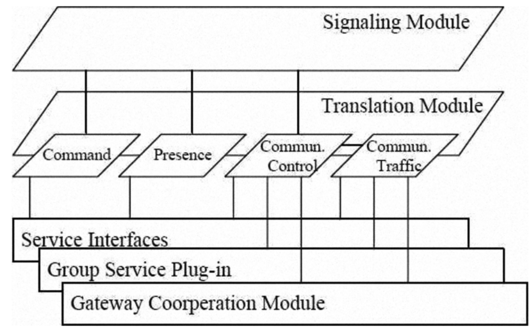

Fig. 3. The personal gateway

7) Group service plug-in: When a user is also a member of some groups, it is possible for group entities to provide the user with group services. There are some limitations on these services: first, they cannot be directly integrated in PUCS because they are not public; second, the particular services related to a group cease to be available when a user ceases to be a member of the group; and third, the user can use these services only when he/she is using or contacted with an alias as a member of the group (or be directly addressed with the terminal addresses of these services). In other words, if the user is contacted with the UPI, he/she should only be able to use these public services other than the group services.

These group services can be integrated into PUCS via the group service plug-in (GSPI) defined in both the PPS and PGs. If a user is using a group service, there should be a control module attached to the GSPI on the PPS. For example, since *Jack* belongs to *PUCS-ABC*, he needs to integrate a specific control module on GPSI to implement controls of extra group services specifically for the company, such as an internal IM system or an internal audio/video conferencing tool. If the PPS receives a communication request from other PPSs to a group member alias (such as *working@jack.PUCS-ABC.com*), or from GSPI on the PGs of the user (when the request is sent to a terminal address of the group service), it will ask GSPI whether there is a control module that can be used to determine how to process this communication request. If the control module cannot process the request, it may choose to ask the service coordination module to handle it by public services. In another words, the communication session may be established from a group service terminal (at the caller side) to a public service terminal (at the receiver side). The communication translation and cascade connections are implemented on a PG based on the instructions of the service coordination module. The user may define which public service can be used for each specific group communication in the profile module.

B. Personal Gateway

While the PPS handles the UPI addressing/identification issues and communication control of the user, PGs serve as gateways for different communication service networks that provide the practical communication integration for the user. Generally, a PG can establish communications between itself and a user

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terminal, between itself and a terminal that is not of the user's terminal, or between different PGs of the user.

When a user want to access PPS to perform tasks via a specific terminal such as querying personal information, configuring personal settings, or initializing a call based on UPI, he/she must establish the communication session between the terminal and a PG. The PG will then further process the commands via a command module and forward the commands to the PPS using appropriate signalling messages.

When a caller wants to make a call to a terminal of the user, this request may be caught by a PG of the user first before it reaches the terminal. Then the PG can forward the request to the PPS to determine whether the communication session should be processed at the requested terminal address, or at another terminal address which is more appropriate (especially if the user is not available at the requested terminal address). If the decision is to set up the communication session on another terminal and different communication services are to be used on the two end terminals, then two communication sessions will be established - one from the caller's terminal to a PG and another from the PG to the user terminal desired to handle the communication session. If different PGs are used in these two communication sessions, an extra communication session will be established between the PGs.

Another feature provided by the PGs are the presence watching/tracking function. The PGs should be able to track the presence information of each terminal of the user so that it can ask the PPS to update its presence information for the user.

1) Service interfaces: The service interfaces are essential parts of the whole PUCS system. The PGs should have at least one service interface for each type of service which must be integrated in the PUCS. The service interface has three functions. First it provides the communication capability between the user's terminals and the PGs. Second it tracks the presence information of terminals. Third it catches the communication requests from other people's terminals to the user's terminals. The implementations of the service interfaces are different for different services. Here we just give an example for the IMS mobile communication service.

In IMS, presence tracking can be done easily when a service interface is registered as a watcher to all terminals in the IMS. To implement the communication capacity between PGs and IMS terminals, some terminal addresses must be bounded to the service interface. Normally we suggest binding a home phone with the service interface to implement all communications between PGs and any terminals which can make telephone calls. This allows any terminal to simply call the home phone number and the communication request will be answered by the service interface instead of the home phone. Extension numbers can be used to indicate the purpose of the communication request from the calling terminal. For example, it can be "0" or no extension for communication with home phone, "1" for communication with the service interface, "11" for UPI-based communication initialization, "12" for command interface access, "13" for presence registration/update, and so on. However, if such binding is not possible, a special software can be installed in mobile terminals as a mini PG so that a service interface can be implemented on the IMS terminal. The communication between a terminal and the mini PG on it is straightforward.

Other communication services such as GSM mobile communication service, IM, and SIP over wireless networks can also be integrated in PUCS by specific service interface implementations. Due to space limitation, we will not discuss the details in this paper.

2) Presence interface: The presence interface is used to receive presence updates from the service interface and translate them into signalling messages by the translation module before forwarding them to the PPS.

3) Command interface: The command interface is used to accept different commands from the user's terminals and translate them into signalling messages by the translation module before forwarding them to the PPS. It should support different types of commands. Specifically, a speech command interface and a text command interface must be implemented. The command interface enables a user to check and update his/her profile, update the alias and any other configurations, or initiate a UPI address-based communication request.

4) Communication control module: The communication control module is used to receive communication requests and other messages from service interfaces and translate them into signalling messages before forwarding them to the PPS. Also, when the communication control decision is made by the PPS, a signalling message will be sent from the PPS to the communication control module so that the communication session can be established according to the decision. Generally, the communication control module functions as the brain of PGs.

5) Communication traffic module: When a communication session is established as two cascade communication sessions, i.e., from caller's terminal to one service interface and from another service interface to the user's terminal, the communication traffic module is used to translate communication traffic between the two service interfaces for the communication session. The translation is configured by the communication control module. If the two service interfaces are not in the same PG, the involved PGs must communicate with each other. The communication traffic module also needs to translate the communication traffic into the standard format which is used to transmit messages between PGs.

6) Translation module: The translation module performs the translation between different data types. It is used by presence interface, command interface, communication control module and communication traffic module.

7) Gateway cooperation module: If the service interfaces in different PGs are used to establish cascade communication sessions to perform one communication task, the gateway cooperation module is used to exchange communication traffic between different PGs.

8) Signaling module: The PG also has a signalling module, whose major function is to implement the communications

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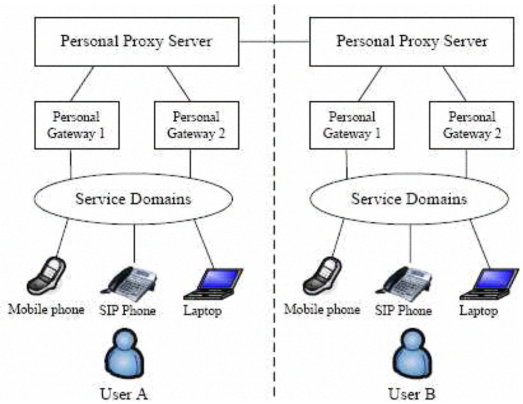

Fig. 4. Interconnection

between PGs and the PPS.

9) Group service plug-in: Like the GSPI module in PPS, the GSPI module in a PG is responsible for the integration of different group communication services. All the interfaces for any group services must be attached to GSPI.

C. Deployment of modules

Unlike other UC systems, the PUCS is a personally operated system; so we need to discuss how to deploy their components. Generally, the PPS only exchanges signalling messages over the Internet. So it can be located on either a dedicated server at the user's home or on a shared server at any data centre. The deployment of the PG is more difficult since it needs to provide service interfaces for different types of services. To effectively utilize the communication services of the user, it is preferred to deploy the PG in a distributed way. For example, as discussed in III-B1, a PG can be implemented in a user's IMS terminal, so PUCS can utilize the user's terminals as the service interface. With this distributed deployment, different PGs must have the gateway cooperation modules to communicate with each other to implement any-to-any communications. Fig. 4 shows the interconnection between different PUCSs which have distributed PG deployment.

IV. Application Examples

In this section, we first present an example to show how the proposed PUCS can be used to integrate different wireless communication services for a user and also how it can be used to provide group UC services for the user with GSPI.

We assume that *Jack* is using two public communication terminals. One is an IMS mobile phone and the other one is a laptop which subscribes to an IM service via a wireless network. There are also two group services provided to *Jack* and integrated to *Jack*'s PUCS. One is an internal IM service, the other is an audio conferencing tool. A communication control module and a communication interface are implemented behind the GSPI modules on the PPS and PGs. When a caller wants to send an audio conference request to *Jack*, the caller first sends the request to *Jack*'s internal IM account. The request is caught by the communication interface behind the GSPI on a PG and forwarded to the PPS. The PPS will call the communication control module behind the GSPI to handle the request. According to *Jack*'s presence information and profile of the group, if *Jack* is not available via the internal IM service, the communication control module forwards this request to *Jack* via the public IM system. The request is sent back to a PG with the instructions on how to handle it. Then the communication control module on the PG sends out the request to *Jack* in the public IM system. *Jack* then receives the request on his public IM account. We assume that the request includes text descriptions and a URL for answering the call. When *Jack* accepts the request by clicking the URL, the audio conference server starts an audio call to *Jack*, which is supposed to be received by *Jack*'s audio conference client software on his working computer. This audio call is caught by the communication interfaces behind GSPI in a PG and then forwarded to the PPS. The communication control module behind the GSPI on the PPS then finds that *Jack* is not available on the conference client. So it tries unsuccessfully to find an in-group audio communication service to handle the request. Then it tries to find a public audio communication service to perform this conference call. If *Jack*'s mobile phone is on, the control module asks the communication control module in a PG to set up a communication session between the PG and the mobile phone. Also, it asks the communication interface behind the GSPI in a PG to accept the conference call. Then, the audio conference communication session can be established with two (or three if two PGs are involved) cascade communication sessions. If the mobile phone is not on, the communication control module behind the GSPI on the PPS may try to use the public IM service to handle the conference call. The translation module is used here to support audio-text communication.

This example shows how a group communication request can be handled by PUCS intelligently. The communication task can be done even if the user does not have the communication capability required by the original communication request. Generally, the use of PUCS allows the user to have many unified communication capabilities (i.e., not limited to those presented in the example). PUCS uses its PPS to provide communication control, specifically through the PPS service coordination module. So communications can be handled flexibly and intelligently. The PUCS provides rich presence services and the presence of the user on different service domains can be coordinated so that it can be used by any communication partner. PM is one of the key features of the PUCS. A user can use any communication terminal in any service domain. As long as the service is integrated into the PUCS by a specific service interface, the user can be contacted by his/her UPI or aliases. Furthermore, even if the caller is not using the UPI but a terminal address (such as a telephone number or an IM account name), the user can still be reached if he/she is not available on that terminal. Any-to-any communication can also be supported by PUCS. Suppose that a caller initializes a communication session to the UPI of the user. Irrespective of the communication type it is, the

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PPS can manage the communication session so that the call can be forwarded to the PG and further translated into the required type of communication service before reaching the user terminal in that service domain. The PUCS system also provides command interfaces such as speech access. The user can call a PG first and then use the command interface to initialize a UPI-based call, to access the profile server and to do other server querying and configuration tasks. A particular advantage is that the command interface gives the user the capability to call a terminal which is of different service type from the user's calling terminal. Other features like unified messages can also be supported by PUCS easily.

PUCS has some very particular advantages over previous solutions for UCs which can be used over heterogeneous wireless networks, such as ENUM, UCI, and IMS. The PUCS provides a single identifier (i.e., the UPI) for a wide range of services (i.e., the same as EUNM, UCI, and IMS). It can identify the terminal address of UPI and allow the authenticity of any association between a terminal address and a UPI (UCI and IMS have the same capability but ENUM can only support one-way authentication). Furthermore, the PUCS provides a calling terminal with the capability to call to a specific terminal address of a different service type as the calling terminal (ENUM, UCI and IMS do not support this feature). PUCS hides the mapping between UPI and terminal addresses in the personal modules (UCI and IMS provides a similar protection but ENUM does not). The PUCS is a more scalable solution as compared to other solutions. Note that the PUCS is implemented in a personal domain so it does not require modifications of any service provider networks (ENUM, UCI and IMS need modifications of service provider networks). Also, since the PUCS is a personal system around individuals, it can be employed by individuals flexibly (e.g., based on their needs) and different services can be integrated only when they are applicable to a user (for UCI and IMS, to implement a global service, every involved service provider network must be modified to support the service). Last but not least, in the PUCS, third party services can be easily integrated through GSPI at a low cost, since the PUCS is operated by individuals rather than the service providers (in UCI and IMS, such an integration may be complicated and expensive).

V. Conclusion

We have proposed a Personal Unified Communication System (PUCS) for handling complicated communication services on heterogeneous wireless networks around a user. In contrast with other solutions, our solution focuses on individuals rather than a service domain or a group domain. PUCS provides PM, any-to-any communications, user presence, IM, unified messaging, speech access and text access. All these functions are implemented by a PPS and some PGs for each user. The solution is scalable since it is implemented in personal domains. Moreover, PUCS provides a flexible way to integrate group services to create a group UC environment for PUCS users. In such a way, a user can belong to different groups and enjoy different UC services in different group domains as well as in the personal domain. For future work, we shall implement a prototype PUCS and evaluate it in different situations under practical conditions.

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