Spatially aware local communication in the RAUM system

Felix Hupfeld, Michael Beigl

Universität Karlsruhe, Telecooperation Office,
Vincenz-Prießnitz-Str. 1, D-76131 Karlsruhe, Germany
{hupfeld, michael}@TecO.edu

Abstract. In this paper, we propose a new paradigm for local communication between devices in Ubiquitous Computing environments, assuming a multitude of computerized everyday appliances communicating with each other to solve tasks. This paradigm is based on the concept that the location of devices is central for the communication in such a scenario. Devices define their communication scope by spatial criteria. In our paradigm no explicit addressing or identification of communication partners is used. In comparison to traditional communication methods the approach eases routing and discovery problems and can be deployed in a highly dynamic environment without centralized services. We use the term local communication as inter-device communication in a physically restricted local area. This is well distinguish from the terms telecommunication as communication over distance where location information is explicitly hidden. The communication model (RAUM) introduced is based on the observation that humans structure their environment primarily spatially. We show that spatially aware communication, is an efficient method communication in ubiquitous computing environments. We relate the communication architecture of the OSI/ISO reference architecture. An exemplary implementation that realizes a context information system is described. Based on this system several applications (Smart Doorplate, Communication with peripheral devices) have been implemented and evaluated.

Introduction

In the vision of "ubiquitous computing" devices and humans obtain access to any information everywhere [Weiser, 1991]. This vision is implemented by many research projects like Stanfords Interacive Workspace [Fox et al., 2000] or GMDs iLand [Streitz et al., 1998]. A further class of systems is based on the idea that there are services and information, that is not location bound, that should be ubiquitously accessible, e.g. database access and web-pages. For example, in the ParcTab project [Want et al., 1995] information in the Internet, e.g. a text document or e-mail at your "home server", are accessible from everywhere around the world with the help of small devices. This prototype can be considered as an ancestor of the upcoming WAP-enabled devices [WAP] or Internet enabled Personal Digital Assistants (PDAs) as 3COMs PalmV, that allow Web-access or access to a virtual "home base" via Internet.

Other ubiquitous computing systems provide local information for global access. For instance in the Olivetti ActiveBadge project [Harder & Hopper, 1995] stuff was wearing electronic badges. These badges are tracked by a location system and the processed information is then presented on the Web. Using the SmartBadge [Beadle et al., 1997] even context information collected from sensors on the badge are accessible to internet users.

An example for a project addressing the research on context information is Georgia Techs Aware Home project [Kidd et al., 1999], where a house is equipped with context retrieving sensor systems. A great part of such context information is not of interest for a user or machine outside of a spatial scope, but builds the basis for “local” application. We have identified location as the most important context for communication of computer-augmented devices in ubiquitous computing [Beigl]. This kind of local communication is different from telecommunication and will be explained next. The architecture and experiments with the system will then give a closer insight into the RAUM-system.

Types of Communication

The challenges in telecommunication of the last decades were primarily to enable people to communicate over great distances independently of their location. As the prefix suggests, tele[1]communication is about remote communication. Telecommunication system abstract from the location of the communication partners.

The use of a telecommunication system arises from the need to communicate with somebody or something who or which is not physically present at the location of the caller. The communication partners (more precise the end-systems) are chosen by their **identity**, e.g. if you pick up your phone, you want to call a specific person whose identity is represented by her or his telephone number. The same applies to device telecommunication, here using the Internet. The first criterion for selecting the remote computer system is its identity represented by the IP address or the DNS name and then choosing the service. As a consequence parameters as the **physical location** of the partners are **hidden** from the user and from the end-system by the telecommunication system.

Local Communication

We regard communication between partners that are located in the same physical space as **local communication.** We consider the same physical space as what is perceived by a human as "environmental" [Montello, 1993] or local to the device. Local communication is carried out not only between humans but also between machines in **interactive rooms**. Such interactive rooms are equipped with (invisible) computer systems everywhere in the environment:

[1] Tele- is Greek for remote

Interactive rooms are places where the environment and many artifacts of the everyday live are extended with computer and communication technology.

Local communication supports this by providing a basic communication that is easily understandable to the human and flexible in its use without administrative overhead. In local communication partners (e.g. computerized artifacts) are selected according to their spatial co-location and not based on their identity. This selection process does not require any user interaction or administration. Services or information, which are requested by one device, are retrieved through communication to devices nearby. In this form of communication access to and from devices outside the local environment is not supported.

Spatially aware communication

The importance of the spatial relationship is obvious in human communication: If you want to talk to somebody, you stand in front of him. When you're talking, you neither want to communicate with a person behind you nor with a person in another room. Furthermore, the identity of the person you are talking with is of less importance. Your scope of communication is the person next to you.

This kind of spatial communication relationship is transferred to communication of computerized devices. As with humans, the spatial relationship defines an area of interest based on the spatial layout. As recent findings in cognitive science suggest, that for humans space is central for the understanding of interaction and communication [Kirsh, 1995]. Considering the involvement of humans for local communication, human understanding of the communication process is important. In interactive rooms application developers and users will benefit from the human understanding of communication [Brooks, 1991]. Our research suggests that such an understandable and efficient form of human-like communication is also efficient for device communication.

In spatially aware communication devices use location as their primary attribute for selecting potential communication partners. Devices describe a scope of interest in which they are willing to communicate depending on the current state of the application running on the device. By doing so the communication simulates the communication behavior of humans. Only communication from partners inside a scope is accepted. At the end of the paper we describe some example applications, that are build upon such communication paradigm.

Service oriented local communication

Location awareness is important for the communication of local devices and applications, as it was shown in the examples above. Beside from building a new kind of communication system we can achieve this goal by using existing communication technology: a service-oriented telecommunication system enhanced with a lookup service or an infrastructure as in Jini or T-Spaces. As we mentioned before, the location information is hidden by these telecommunication systems. It has to be reintroduced and modeled explicitly via a service. This service must be able to track the location of each device and to select communication partners by spatial layout. See [Maaß, 1997] for a system architecture of this kind.

This solution has several drawbacks. First, the usage of a telecommunication system introduces a first indirection. The devices are mobile, thus a dynamic mapping between the device identifier and its position has to be made for routing packets. The network has to know in which subnetwork the device is located in order to forward the packets there. The central property of local communication, the device location, is hidden at first and then reintroduced explicitly through a service. This introduces (apart from the overhead caused by the lookup) a second indirection. A device position is mapped to a network address, which has to be mapped back to a position (i.e. routing information) for delivery. This makes the system inefficient and depends on dynamic mappings, which have to be set up and kept up-to-date. [Beigl, 1999] shows that the more devices take part in such a system and the more complex the system is (in terms of communication scope extension), the overhead introduced this way is rising against the spatially depended communication system we present here.

Additionally, the reintroduction of the location in a telecommunication system requires a service rendered by a central server in current systems which introduces the problems of service discovery, configuration/administration and availability.

Using telecommunication systems for local communication introduces a large overhead. A genuine location-centric local communication system foregoes the problem of routing packets to mobile devices due to the fact that the message identifies the position of the targets. Thus no techniques such as mobile IP, stemming from implicated locality of the IP address system, need to be employed to be able to route the flow of information to a device in a constantly changing network topology. It does not depend on a central service to define the spatial communication scopes, which introduces the problems of service discovery, automatic configuration and availability.

RAUM[2]-Architecture

The RAUM-architecture describes the communication stack and the protocol for artifacts and optional communication infrastructure. The RAUM-system presented here is based on the RAUM-architecture and allows artifacts in interactive rooms to communicate either with or without infrastructure in an ad-hoc manner. The RAUM-architecture is modeled after the abstract concept of spatially dependent communication [Beigl, 1999].

The RAUM-concept describes the communication of devices according to their spatial relationship in the physical world. Devices define regions of interest in which they communicate (RAUMs). Such RAUMs describe a congruent geometric space in the physical world; the geometric space is defined as a envelop over all points defin-

[2] location-based **R**elation of **A**pplication objects for communicating **U**bicomp event **M**essages. In German the word *Raum* stands for space as well as for room.

ing the RAUM. Because the communication order in the RAUM-concept is bound to the physical location of the objects taking part in the communication, objects that are inside the space of interest are also inside the communication scope of the object defining the RAUM. Every device that is physically located inside the envelop of a RAUM (or more precisely: where the location is related to the set of points in the physical space) is then a member of the RAUM.

OSI/ISO No.	**RAUM System Layers**	**Functionality**
7	Application Layer	Application
4-6	RAUM Event-Layer	Reliable service, world modeling, abstract presentation of packets for application
3	RAUM-Layer	Implements the core functionality of the RAUM system
2/1	RAUM Communication-Layer	Non-reliable packet broadcast and physical transport

Fig. 1. Stack architecture of the RAUM system

The architecture of the RAUM system is layered and can be related to the one defined in the ISO/OSI model. The major functional operations for communication within the RAUM model are concentrated on layer 3, the RAUM-Layer.

The complete stack of the RAUM-System consists of 4 layers (see Fig. 1). The lowest layer is called "RAUM-Communication-Layer" and groups the physical and the DLL layer (ISO/OSI layers 1&2). The current definition of the RAUM-architecture does not specify this layer. Instead existing implementations of DLL and physical layer are used. The RAUM-Layer is responsible for the creation and dissolution of communication relationships, for device location and routing of packets. Communication relationships in the RAUM-system are created according to the definition of a spatial area, the RAUM. Note that these RAUMs are not restricted to the physical broadcast space of the medium.

The next layer, the RAUM Event-Layer, spans the layers 4 to 6 providing reliable communication and eventually offering abstract event communication services to the application, that resides at layer 7. The rest of this section will focus on the RAUM and RAUM-Event-Layer, but first the run of the RAUM-system is explained in more detail.

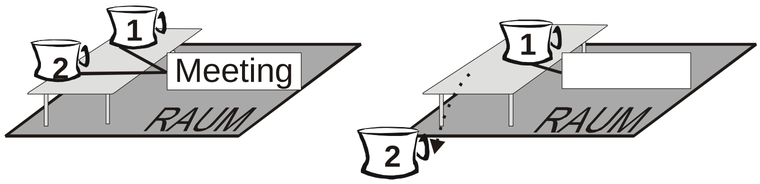

Fig. 2. Example of RAUM communication

Run of a RAUM-communication

The communication of the RAUM-system is datagram oriented. Applications running on the devices send datagram packets to every RAUM they belong to. At the application and RAUM Event-Layer these packets are called **events**. Figure 2 shows an example run: A doorplate defines a RAUM where it wants to receive events from. After definition it gets all events from the two cups (left) inside the RAUM. As one of the cups leaves the RAUM (right), only the remaining cup keeps sending events to the doorplate.

As it is not possible to technically prevent the doorplate from hearing also events from cup 2, the RAUM protocol has to shield the application from these unwanted events. Therefore every object keeps a list of RAUMs which he is belonging to, and a list of all RAUMs it has defined. According to this list the RAUM-Layer decides if a packet has to be ignored or to be processed.

To allow a flexible handling of events adopted to the application needs we had defined three kind of RAUMs:

? Listener-RAUMs: With this kind of RAUM only the object that has defined the RAUM receives all events from all objects inside the RAUM. In the above example the doorplate defines such a Listener-RAUM
? Speaker-RAUMs: If an object defines a Speaker-RAUM all objects inside the RAUM receive all events from the speaker (the defining object). An example of a Speaker-RAUM is a Location-Beacon that constantly sends its location into a certain area.
? Discussion-RAUM: In the Discussion-RAUM every object inside the RAUM receives every event from all objects in the RAUM. This kind of RAUM is needed to allow negotiation with devices in an unknown environment.

RAUM-Layer

The purpose of the RAUM-Layer is to decide whether a received datagram is to be passed on for the user application or to be discarded, according to the RAUM model.

As defined in the previous section, RAUM packets are accepted if the potential receiving device and the datagram packet itself are located inside the same RAUM. This is a purely geometric requirement.

```
Identifier open_RAUM([Name], Rtype, Shape, Relative )
close_RAUM( Identifier )
change_RAUM( Shape )
send( Packet )
Packet receive()
```

Fig. 3. The interface to the RAUM-Layer

To allow such a test, every packet sent must be mapable to a geometric position and every device has to know its own position in space and be aware of the defined RAUMs it is located in. Our devices have a built-in facility to detect their geometric location via a location system (e.g. our IR-Beacons), so they know their location and can tag broadcasted datagram packets with their current position. Device position information is handled by a subsystem called the *Locator service* whose instances communicate with the RAUM Location Protocol (RLP).

The RAUMs themselves are named and defined geometrically by a sets of points. Currently, unions of spherical and cubic shapes are possible. The RAUMs are either stationary or moving with the device that is defining that RAUM. The interface to layer 3 provides upper layers with functions to open and close RAUMs. New or updated RAUM control information is broadcasted to all other devices via the RAUM Information Protocol (RIP). RAUM management is done by a subsystem called the *RAUM service*. Data is exchanged via the RAUM Data Protocol (RDP).

Routing

If devices use different media for communication or the broadcast area of the medium does not allow direct communication between devices coupling of network segments is needed. This coupling enables for example a PDA with infrared communication to interact with an ordinary network printer or an application running on a desktop computer.

Every medium with its limitations forms something like a logical Local Area Network (LAN). This is not exactly the original LAN concept, but every range-limited medium can be thought of as a network in a local area. For example, the infrared (IR) communication in a room form a LAN, as all IR transmitter-equipped devices in the room can communicate, but no information reaches other rooms. Low power radio frequency (RF) transmission and especially cable networks like Ethernet are other examples. Each LAN covers a specific geometric area, for example the room the wireless transceiver is in or the spots where devices are connected to the Ethernet. The regions covered by these LANs can overlap, and thus a certain area in a room can be supplied by several media (Figure 4).

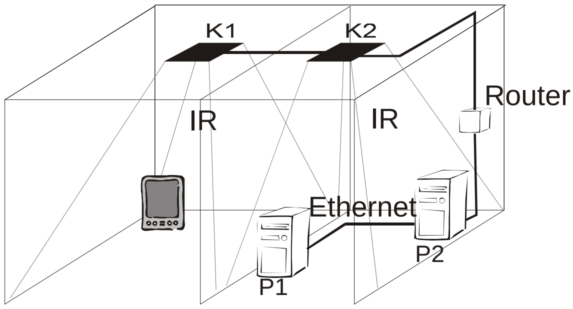

Fig. 4. Infrared and Ethernet networking

To allow the inter-medium communication mentioned above, these LANs have to be coupled with devices connected to some type of infrastructure giving them access to the other LANs. This coupling is similar to inter-LAN communication in telecommunication systems. Because there is no explicit addressing in RAUM communication location information of the communication packets is used for routing. The location information paired with the RAUM definition results in an addressing concept where the location is congruent to the address in local communication and which can be used for routing decisions. Such a router caches all communicated RAUM definitions of adjoining LANs. Furthermore the component knows the physical dimension of theses LANs, too. Using this information and the fact that RAUMs are geometrical objects it can be decided which packets from one network interface should be forwarded on the other. RAUM packets are of interest to a LAN if the described RAUM intersects with the area the LAN covers, so they must be forwarded in this case. Packets must be forwarded into a LAN when any of the devices there should receive it, for example when a RAUM covers the geometrical areas of both LANs. So the communication stack has to check all RAUMs in this LAN to see whether the packet is inside. Position information of a distinct device is needed in a LAN when a packet from it has to be routed. Therefore location information has to be associated with every packet send.

4 Application examples

The RAUM system is currently used for inter-device communication in our research in Ubiquitous Computing. The RAUM stack runs on desktop computers, Palm Pilots and PIC microcontrollers [PIC]. Several routers couple the different media with an infrastructure of infrared, radio frequency, CAN and Ethernet transceivers. There are several LANs with numerous IR spots, RF areas and an Ethernet in several rooms. We built several applications, some of them are used to yield context information for applications in human computer interaction. We describe here two of them, more can be found in [Beigl &Gellersen, 1999] and in [Beigl, 1999].

4.1 The Context-Aware Doorplate

The context-aware doorplate (SmartDoorPlate) displays the name of the room, the names of the people working in that room, or events taking place there (e.g a meeting is in progress in this room). The information for recognizing a meeting in progress is inferred from the context established by MediaCups [Beigl et al., 2000]. The MediaCup is a computer-augmented coffee cup with infrared communication, which distributes status information such as temperature and usage in specific time intervals.

The doorplate application defines a RAUM with the same shape as the room it is related to. In our set-up the plate is mounted next to the door and waits for context information emitted in events by MediaCups. These events get packed into RAUM datagrams and sent out via the infrared link. Every other infrared device within range, i.e. every other device in this LAN, receives the packets. The router device, which has a transceiver in every LAN, receives them, checks for the extension of the defined RAUMs and routes them to the appropriate LANs, here the Ethernet. The communication stack of the doorplate application receives them and puts them into the recognized "world", a storage space where the RAUM Event-Layer puts all information of interest into. Events of interest are expressed with the receive operator. The doorplate is able to track the presence of MediaCups in the room this way, and thus can infer from this context to an ongoing meeting.

Writing an application using the spatial awareness feature based on local context can be done easily in a natural way, because the communication stack holds all important information for it. When setting up this application using the RAUM system, the doorplates define a RAUM with the same spatial dimensions as the conference room they are monitoring. The cups in turn are set up to emit their data as messages sent to this RAUM. With this simple setup, using just one RAUM per conference room, it is possible to implement this application; the pseudo code of the smart doorplate is shown below:

```
MyRoomShape := Sphere (x,y,z,r)
initializeRAUM (myRaumName, myRoomShape)
world = receive (“Cup, hot, *”)
while TRUE
   int rec_cups := 0
   rec_cups := count_known_objects(world)
   if rec_cups > 2 then printLCD
                            (“Meeting“)
```

4.2 Communication with peripheral devices

A common scenario in local communication is the wireless connection between an appliance and a peripheral device. For example, a digital photo camera has to communicate with a printer or a storage medium on user's request, input devices as a mouse or a keyboard have to be bound to a computer. We built a wireless computer keyboard (AwareKeyboard) which can be used to input text on Palm Pilots. The connection between the keyboard and the Palm Pilot is location sensitive: if you put the Palm Pilot next to the keyboard, you can use it to enter text.

The Palm Pilot defines a RAUM of circular shape around his current location and filters for keyboard event messages. On keypress, the keyboard puts an event in the RAUM system, which, when the Palm Pilot is near enough and thus the keyboard is inside its RAUM, is received by the Palm Pilot:

```
initializeRAUM (PilotRAUMName, Circle (0.5 m))
events = receive (“Keyboard, KeyRelease, *”)
while TRUE
   inject_into_input_queue( events )
```

5 Related Work

The idea of using a telecommunication system paired with a lookup service to do local communication can be found in other systems. Some of them enable devices to select their communication partner by spatial criteria, others simply pass location information to the application. The introduction of location information in a telecommunication environment is usually managed by a central location service, few systems use decentralized facilities. Leonhardt [Leonhardt & Magee, 1998] provides an architecture for acquisition of location information from divers sources. [Leonhardt, 1998] covers the aspects of location-aware telecommunication.

Jini [Jini] of Sun Microsystems is an object-oriented distributed system for inter-device communication. Jini-enabled devices register with a central lookup service where other devices can find them and thus select their partner. Physical location plays no role in this selection process, its focus lies on service compatibility.

[Maas, 1997] describes an architecture which is similar in functionality to the RAUM system. Location information is introduced in a telecommunication system via a central location component, a directory service. The directory service allows clients to retrieve communication partners by several different spatially dependent criteria such as distance, type and special conditions, devices can be located and clients can get notified when given devices meet or enter an area. Hive [Minar et al., 1999] of the Massachusetts Institute of Technology is a system for device communication modeled after the Agent paradigm. No central services are used. Devices are modeled as cells, their functionality is bundled in so-called shadows. Active Agents move between those cells and are enabled to do location dependant communication tasks by semantic models.

The routing in the RAUM system between the interconnected LANs is based on this „location addressing“. The aspect of using location information in the addressing scheme in WANs (wide area networks) is studied in [Navas & Imielinski, 1997]. Here, IPv6 addressing is combined with geographical information from GPS (global positioning system) to aid in routing. [Ko & Vaidya, 1998] describes a routing scheme which uses location information as an aid in routing, too.

6 Conclusion and future work

We introduced the term local communication, contrasted it to telecommunication and showed that location-based communication is more suitable to human needs and to local communication topics. Such location-based communication is best suited for interactive rooms where a multitude of computerized artifacts are communicating with each other to carry out tasks mostly without direct user interaction.

The presented RAUM system is an example of such a location-based communication system. The architecture of the RAUM system is layered and can be related to the one defined in the ISO/OSI model. The major functional operations for communication within the RAUM model are concentrated on layer 3, the RAUM-Layer. In this layer delivery and reception of packets according to spatial areas (RAUMs) and routing of packets is handled.

The RAUM system and applications implemented on top of the system are in usage in an everyday environment since September 1999. The experiences collected with the RAUM system and with the applications indicate that the chosen communication paradigm is efficient in the given environment and allow us to identify areas of further work: Human-Computer Interaction (HCI), Appliance (Hard- and Software) design and networks. In interactive rooms HCI issues are very critical: In Appliance design the focus is on energy safe design. Energy saving protocols (e.g. [Tsaoussidis et al., 1999]) make an important contribution in that area.

Our current setup shows the advantage of using location-based communication for local applications. Further work will investigate how location-based and telecommunication can be assembled to provide the appropriate communication basis for different application tasks. Also the routing algorithm will be extended to allow for more flexible routing and load balancing. Work on the RAUM architecture will research on the lifetime of events in RAUM-communication and on supporting applications with a rule-based language to describe situation-reaction pairs.

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