Accessing Ubiquitous Services Using Smart Phones *

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Abstract

The integration of Bluetooth service discovery protocol (SDP), and GPRS internet connectivity into phones provides a simple yet powerful infrastructure for accessing services in nomadic environments. In this paper, we discuss the design and implementation of SDIPP, a protocol for provisioning services on Smart Phones. Although several service discovery protocols have been proposed earlier, such as SLP, Jini, UPnP, Salutation, they all have their own infrastructure requirements and target audiences. Bluetooth SDP is an on-the-fly service discovery protocol. However, it is not nearly as powerful as its counterparts. SDIPP works by augmenting Bluetooth SDP with web access and personalization. Payment of services has been overlooked in the protocols proposed earlier. SDIPP provides a novel protocol for anonymous payment, based on the idea of Millicent scrips. We have implemented a few services to illustrate our protocol. We report on our experiences and experimental results. In particular, we analyze and provide an application level solution to the Bluetooth inquiry clash problem that was discovered in the process.

1 Introduction

Smart Phone technology is a result of the convergence of cell phones and PDAs and is steadily becoming ubiquitous with all the big mobile manufacturers like Nokia, Sony Ericsson and Motorola vigorously supporting it. Despite efforts by giants like Miscrosoft and Palm, and presence of Linux based Smart Phones like Motorola A760, Symbian OS remains the most dominant platform for Smart Phones, holding 67% of the market share which is expected to grow. Symbian OS supports Personal Java, J2ME, MIDP as well as C++. With ample memory and computing power, Smart Phones are expected to personify the *abstract handheld* that has so long been part of the picturesque visions of pervasive computing [30]. Many believe that Smart Phone technology will be instrumental in guiding and realizing the visions of pervasive computing, by giving shape to abstract ideas and assumptions.

Several service discovery protocols have been proposed, such as SLP [19], Jini [28], UPnP [10], Salutation [8], Bluetooth [9], DEAPspace [22], Intentional Naming System [12], Secure Service Discovery Service [16] and Splendor [31]. These protocols can be roughly classified into two categories: *client-service* model and *client-service-directory* model, with the exception of Splendor which follows a *client-service-proxy-directory* model, where *proxy* is used to achieve privacy, authentication and load-sharing. In *client-service* model, clients directly query services. In *client-service-directory* model, clients query directories which cache service information. While the *client-service* model requires less infrastructure and is more suitable for nomadic environments, it is not nearly as powerful as the *client-service-directory* model. For the widespread deployment of one or more of these protocols, clients and directories should take a form acceptable by end-users. We take the stand that Smart Phones are suitable candidates for clients and build our solution around this assumption.

Bluetooth SDP has been incorporated in Smart Phones and follows the *client-service* model. Without any additional infrastructure, it can be augmented to support the *client-service-directory* model by exploiting GPRS connectivity on phones. In our solution, therefore, directories take the form of web servers. Directory lookup has additional cost associated with it (in terms of both time and cost of downloading data from internet) and its usage should be minimized.

Bluetooth SDP does not address post-discovery client-service interaction. Client-service interaction involves: (1).

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obtaining the interface for communicating with the service and (2). paying the service, in case the service is profit-based. Payment should not be a part of the service interaction protocol as services are assumed to be untrusted. The service discovery protocols proposed earlier overlook the payment aspect of service provisioning.

A traveler walking/driving down a street with several restaurants by the side may want to order food using her phone without having to obtain numbers and calling up every restaurant. She may also want to schedule a pickup or delivery. In the pervasive computing world, the restaurants may install devices for receiving orders and payments at different locations. The user would query for *food services*, and obtain a list of services that match her preferences stored on the handheld. She would select a service and automatically obtain, on her handheld, the interface for communicating with the service. After placing the order and specifying pickup/delivery details, she must pay for the service. Instead of using a credit card for such transactions, she may prefer to use an anonymous payment system for privacy reasons.

Similarly, a person lost on a highway may want to avail of a service that provides her (prints or dictates) directions to help find her way. Such a service could be installed by a service provider at different locations on the highway.

The services mentioned above are examples of *nomadic profit-based services* and would differ from *non-profit services* or *personal area services* in certain key aspects, such as motivation for their existence, economic models driving them, access and discovery mechanisms, composition and description. *Profit-based* services would not only need strong revenue models in order for them to exist, but also widely accepted and simple to use access mechanisms. While secure payment and dynamic interaction would be issues, composition and interoperability would take a backseat. At the same time, assumptions about existence of any supportive infrastructure for discovery would be unrealistic.

With that in mind, we propose a simple to deploy and minimal infrastructure protocol for service provisioning. The scenarios described above are composed of three overlapping phases: service discovery, service interaction and service payment. We have designed a protocol called *SDIPP* (Service Discovery, Interaction and Payment Protocol) for provisioning services on Smart Phones. We have implemented and tested this protocol on Sony Ericsson P900 phones. SDIPP uses personal information of the user stored on the phone for authentication and service selection and location information to aid service discovery. We have implemented a few applications and evaluated them. In the process, we have learned valuable lessons about Bluetooth which we discuss in the paper. In particular, we analyze and provide an application level solution to the *Bluetooth inquiry clash* problem that was discovered in the course of implementation.

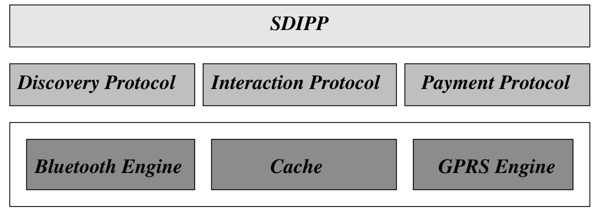

Figure 1. SDIPP Client-Side Architecture

The rest of the paper is organized as follows. In Section 2 we present the SDIPP protocol. In Section 3 we describe two applications implemented on top of SDIPP and present evaluation results. In Section 4 we discuss the Bluetooth inquiry clash problem. Section 5 presents some thoughts and limitations. Section 6 discusses related work. We conclude in Section 7 with directions for future work.

2 Service Discovery, Interaction and Payment Protocol (SDIPP)

From the client's perspective, SDIPP is composed of three phases. In the first phase the services are discovered. In the second phase, mechanism for interacting with the service is figured out. In the third and final phase the user interacts with the service and pays for its usage. While designing SDIPP we tried to answer the following question: how can we best provision services on smart phones?

2.1 Architecture

Figure 1 shows the SDIPP architecture. *Bluetooth engine, GPRS Engine* and *Cache* are the building blocks of the protocols. Bluetooth Engine is invoked by the protocols to discover or interact with the services in the proximity. It is a layer above the Bluetooth stack and provides a convenient Java API for accessing the Bluetooth stack. *GPRS Engine* is invoked to carry out the communication between the phone and the web services over GPRS.

Cache is persistent storage. The personal information of the user along with her preferences regarding services are stored in the cache. Personal information of the user may

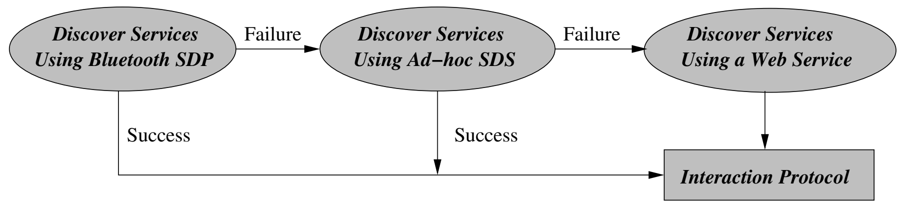

Figure 2. Discovery Model

include name, age, address, credit card number etc. Storing personal information serves two purposes: first, it provides a way of identifying the user and authenticating her if need be; second, personal information along with preferences and location help in identifying the best suited service for the user during service discovery phase.

2.2 Discovery protocol

The discovery protocol is hierarchical and builds on top of Bluetooth service discovery protocol [9] which is *query based* and has already been incorporated in Smart Phones. Bluetooth SDP provides service browsing without apriori knowledge of service characteristics. It does not include functionality for accessing services, however, it can be used in conjunction with any other protocol for accessing services. The discovery protocol is a 3-step process, as summarized in what follows.

One-hop discovery: Services in the proximity (one-hop) are discovered using Bluetooth SDP. If the list of services discovered by Bluetooth SDP includes the desired service, the discovery phase is over. If it does not include the desired service, but instead lists a Service Discovery Service(SDS), the SDS is invoked to locate the desired service in a multi-hop fashion.

Multi-hop discovery: SDS would implement a mechanism for discovering services and could exploit the ad-hoc network for doing so. SDS could be implemented using DEAPspace, SLP, Salutation, UPnP, Secure SDS [16], or Mobile Agents [27] [29] [15]. Effort has been made to map Salutation APIs to Bluetooth Service Discovery Layer [17]. We believe that such mappings would exist between other service discovery protocols and Bluetooth SDP. The other option is to have an ontology based service description layer with bindings to different service discovery protocols.

In an earlier work, we had ported Smart Messages on Smart Phones [26, 25]. Smart Messages are user-defined distributed applications similar to mobile agents that execute on nodes of interest defined by properties. Smart Messages migrate between nodes of interest using content-based routing where content/property is stored in *TagSpace*. *TagSpace* is name-based memory and is composed of *tags*. A *tag* is a $(name, data)$ pair. We use Smart Messages for discovering services in an ad-hoc network. A service is identified by a tag that it creates on the device it runs on, for it to be discoverable by a Smart Message. The tag stores the service description. An SDS implemented using Smart Messages eliminates the need of having directories in the ad-hoc network. If a directory exists it can be exploited but the discovery does not depend on the presence of a directory.

Web-based discovery: If no SDS is listed, the GPRS connectivity on the phone is used to contact a web service that can locate the desired service. The services would have themselves registered on the web server as a way of advertising themselves and would periodically update their information on the web server. This web service would serve as a directory that lists the location of all the registered services around a particular location. We use a simple interval tree representation for storing location and services, however, a better representation would be ontological, which is out of the scope of this paper.

Since downloading data from the internet costs money, directory lookup is the last step in our protocol. The personal information and preferences of the user are stored in the *Cache* on the Smart Phone. The web service lists the services based on user's location, personal information and preferences. Figure 2 summarizes the discovery phase.

2.2.1 Determining Location

The web service that acts as the directory for looking up services, provides information based on the location of the client. There are several mechanisms for determining the location of a Smart Phone. Among the popular ones are Bluetooth localization [11] and GPS. In our implementation, the web directory discovers the location of the user using the Mobile Positioning System (MPS) recently re-

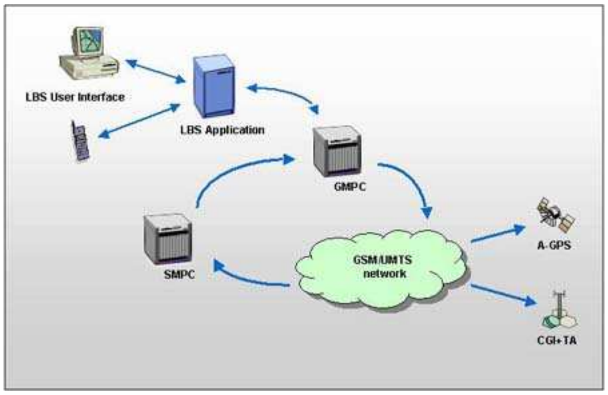

Figure 3. Mobile Positioning System

leased by Ericsson. Figure 3 shows the various components of MPS. MPS consists of a server-based Gateway Mobile Positioning Center (GMPC), a server-based Serving Mobile Positioning Center (SMPC) and software extensions for the operator's mobile network. The web directory is implemented as an LBS (Location Based Service) Application, which can request the GMPC for the position of the mobile phone. After performing an authorization, the GMPC forwards the request to SMPC via the GSM network. SMPC collects position information from the GSM network, converts it to the global coordinate format and delivers the coordinates to GMPC which forwards it to the LBS. Thus by just knowing the MSISDN of the phone (which is passed on as a parameter in the http request), the LBS (web directory) can determine the location of the phone. MPS supports the standardized Mobile Location Protocol (MLP), which is the interface between the LBS and GMPC. MPS supports three types of positioning methods: Cell Global Identity Timing Advance (CGI+TA), Any Time Interrogation (ATI) that gives a low accuracy, and Assisted Global Positioning System (A-GPS) that gives a high accuracy (10 m). For details refer to [3]. Since MPS is provided as a service by the mobile operator, it avoids the need of using an external device like GPS or an algorithm like Bluetooth localization (which requires infrastructure) for determining location of the phone.

2.3 Interaction protocol

In a ubiquitous computing environment, the interaction of the client with a service is assumed to be spontaneous, which implies that the protocol for interacting with the service would have to be learned on the fly. Our interaction protocol is inspired by Jini [28]. Every service registers itself with a web server which assigns it a unique id and stores the interface which can be downloaded for interacting with the service. Figure 4 gives a pictorial view of the interaction protocol. The protocol can be summarized as follows:

- The Smart Phone lists the services discovered during discovery phase. A request is sent to the desired service to send back its unique id over the Bluetooth connection.
- The service responds with its id.
- The id along with the personal information of the user stored on the Smart Phone is sent over to a trusted web server over the GPRS connection. The personal information of the user is used for authenticating her if the service requires that. A weaker form of authentication would be using the IMEI number of the phone, which is a 15-digit unique code that is used to identify a GSM phone.
- The web server after an optional authentication responds with the code and data that will be used for interacting with the service. The code is a Java program which contains the protocol and interface for interacting with the service.
- Since the code is obtained from a trusted server it is assumed to be safe code and is dispatched for execution on the Smart Phone. All further communication between the phone and the service takes place as a result of executing the downloaded code.

Note that the web server(s) for storing the downloadable interface for the services may be different from the web server(s) that act as service directories. We implement downloading of code from the internet using OTA (Over-The-Air) provisioning [6] supported by most cell phone service providers for MIDP.

2.4 Payment protocol

We have designed a protocol for paying services anonymously using Smart Phones in nomadic computing environments, based on the electronic cash representation proposed by the Millicent protocol [18]. There are a number of existing and proposed protocols for electronic commerce such as DigiCash [2], CyberCash [1], First Virtual [4], NetBill [13] and Millicent [18]. None of these protocols has taken off due to lack of supporting infrastructure to implement them in real life.

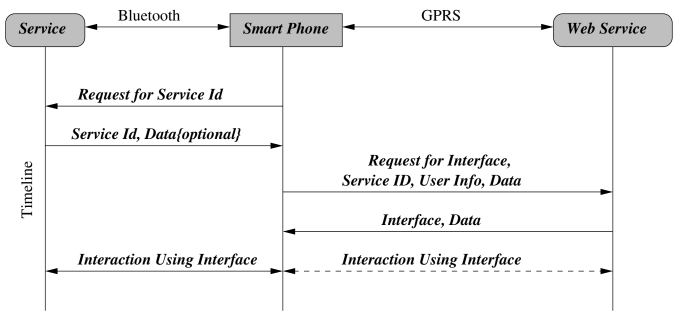

Figure 4. Interaction Protocol

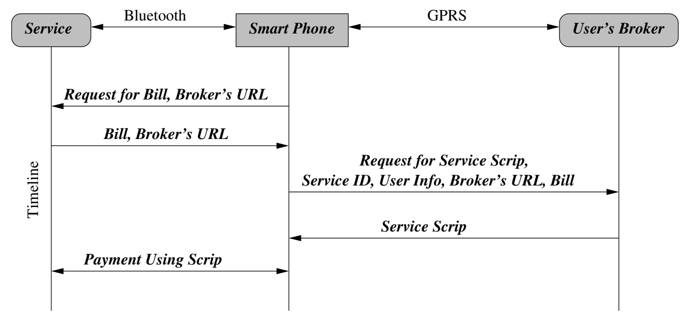

Figure 5. Payment Protocol

Digital cash is normally issued by a central trusted entity (like a bank). The integrity of digital cash is guaranteed by the digital signature of the issuer, so that counterfeiting digital cash is extremely hard. However, it is trivial to duplicate the bit pattern of the digital cash to produce and spend identical (and equally authentic) cash.

Millicent proposes the idea of using accounts based on scrip and brokers to sell scrip. A piece of scrip represents an account the user has established with a vendor. At any given time, a vendor has outstanding scrip (open accounts) with the recently active users. The balance of the account is kept as the value of the scrip. When the customer makes a purchase with scrip, the cost of the purchase is deducted from the scrip's value and new scrip (with the new value/account balance) is returned as change. When the user has completed a series of transactions, he can ”cash in” the remaining value of the scrip (close the account).

Brokers serve as accounting intermediaries between users and vendors. Customers enter into long-term relationships with brokers, in much the same way as they would enter into an agreement with a bank, credit card company, or Internet service provider. Brokers buy and sell vendor scrip as a service to users and vendors. Broker scrip serves as a common currency for customers to use when buying vendor scrip, and for vendors to give as a refund for unspent scrip.

We try to satisfy the design principals described in [23]. In our model, the broker is a web service that the user already has an account with. The vendor is the service that the user wishes to use and pay for.

However, Millicent model assumes that before the customer initiates transaction with the vendor, she either already has the vendor scrip or has the broker scrip which can be used to buy vendor scrip directly from the vendor. Having service/vendor scrip prior to discovering the service would imply that the user already had some knowledge about the service. This is not acceptable in ubiquitous computing scenarios where transactions are primarily spontaneous. Having broker scrip prior to discovering the service is a reasonable assumption to make, however, in order to be able to use the broker scrip, the service should be able to verify the authenticity of the broker scrip which requires additional infrastructure.

Dual connectivity on phones allows the user to bypass both these assumptions because the user can be connected to the broker and the service at the same time.

Figure 5 illustrates the payment protocol. It can be described as composed of the following steps:

- The Smart Phone requests the service for its broker's URL and the bill over Bluetooth connection.
- The service responds with its broker's URL and the bill.
- The service id, broker's URL and bill amount is sent over to the user's broker over GPRS along with the personal information of the user stored on the phone.
- User's broker buys service scrip from service's broker on user's behalf. The amount of scrip bought is greater than or equal to the bill amount.
- User's broker responds to the Smart Phone with the service scrip .
- User pays the service using the service scrip.

Brokers are assumed to be trusted services that have service providers as their clients and other brokers as their peers. Even if the broker tries to cheat, the customer and the service provider can independently check the scrip and detect broker fraud.

Service provider fraud consists of not providing service for valid scrip or deducting more amount from the scrip than

Table 1. Performance Evaluation

Operation	Average Time of Completion
Bluetooth Service Discovery	22.5 sec
Ad-hoc Service Discovery	2 sec $\times$ No. of Hops
Web directory lookup	2.5 sec
Interaction Protocol(Lower Bound)	3 sec
Payment Protocol	6 sec

is valid. If the service provider tries to cheat, the customer can detect the fraud and complain to the broker who will take care of it.

If the customer is cheating, then the service provider's only loss is the cost of detecting the bad scrip and denying service. Every transaction requires that the customer knows the secret associated with the scrip. The protocol never sends the secret in the clear, so there is no risk due to eavesdropping. No piece of scrip can be reused, so a replay attack will fail. Each request is signed with the secret, so there is no way to intercept scrip and use the scrip to make a different request.

This payment protocol provides a security model that is well suited for profit-based services where the service and the user need to be authenticated to each other and anonymity maintained at the same time.

2.5 Bootstrapping

The service registers itself on a web directory (for discovery) and a web broker (for payment). In addition, the service uploads the interface and data needed to interact with it on a web service after authentication and certification. For it to be discoverable by an SDS implemented using Smart Messages, the service creates a *tag* containing the service description.

3 Applications and Evaluation

The SDIPP protocol was implemented and tested on Sony Ericsson P900 phones which have both Personal Java and MIDP in addition to C++. We used MIDP and JSR-82 (Java Bluetooth API) to implement the architecture. Table 1 shows the time of completion for the different phases of the SDIPP protocol. The time of completion of the Interaction Protocol depends on the size of the code downloaded from the internet. The lower bound is determined by the size of the *jad* file of the corresponding code which is typically 250 Bytes. The time of completion of the ad-hoc service discovery over Smart Messages depends on the number of nodes (hops) involved.

Smart Messages(SM) were ported and tested on Sony Ericsson P800 and P900 phones. Personal Java and C++ (connected through JNI) were used to port SMs on phones. While the one-hop round trip time of an SM on HP iPAQs communicating via 802.11b is around 150 milliseconds, the one-hop round trip time of the same SM on P800/P900 phones communicating via Bluetooth L2CAP is around 1.5 seconds, out of which around 1 second is spent on establishing the Bluetooth connection.

Device and service discovery together on an average takes around 22.5 seconds to complete on P900 phones. We noticed irregularity in the behavior of Bluetooth protocol. At least once in every 20 runs, service discovery would fail. Similarly, if a phone has been using Bluetooth radio for a long time, its Bluetooth performance falls and service discovery fails repeatedly (the phone was continually on charge so battery was not the problem). Rebooting the phone solves the problem. This could be due to crowding of service records in the service record database on the phone. But we could not draw any definitive conclusions. The same problems were exhibited while using C++ instead of JSR-82.

We noticed that when two phones are simultaneously in inquiry mode, they become indiscoverable to each other which is due to the fact that, when in inquiry mode the Bluetooth radio bandwidth is completely consumed. We give an analysis of this problem in detail in the next section and offer a solution at the application level. We have implemented two applications to evaluate the feasibility of SDIPP protocol. In this section we briefly describe the applications.

3.1 Restaurant Application

This application was motivated by the scenario mentioned earlier in the paper where a person driving down a road with restaurants by the side wants to order food and pay the bill using his Smart Phone. The service runs on a Bluetooth enabled device installed by the restaurant and can be discovered and interacted with using the SDIPP architecture. The device could be installed by the roadside to make it easily discoverable. When such a device is installed inside the restaurant, or in the drive-through area, it could be instrumental in avoiding queues as many customers could simultaneously place orders through the service. We emulate the device with a Bluetooth enabled computer. The service

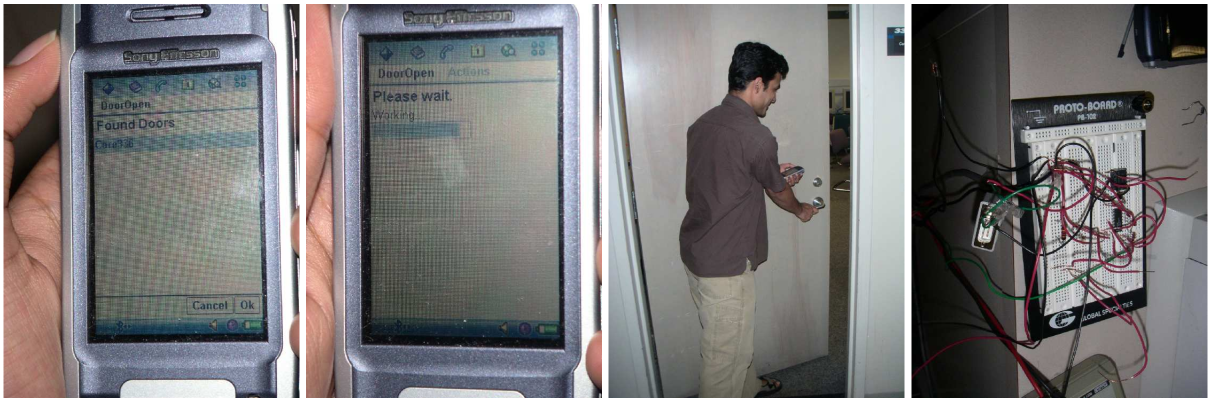

Figure 6. Door Application

registers itself on a web directory (for discovery) and a web broker (for payment). In addition, the service uploads the interface and data needed to interact with it on a web service after authentication and certification. For it to be discoverable by an SDS implemented using Smart Messages, the service creates a *tag* containing the service description.

The user's phone discovers the services using the discovery protocol. The discovery protocol lists the services that match user's preferences. User's preferences are specified as short strings, such as *cheap food* or *Mexican food* under the category of *food preferences* on his Smart Phone and this is matched with the service profile obtained by the discovery protocol while discovering the services. This could be done in a more effective and generic way by using ontologies [24], however, we use our own representation of service profiles for the purpose of this application.

Once the service is selected, the interface and data for interacting with it is downloaded from the internet over the GPRS connection. The code is dispatched for execution which fetches the menu and allows the user to place his order. After the user has placed the order, payment is made using the payment protocol.

Thus, all the user needs, to avail of such a service is the SDIPP architecture on his phone. Payment protocol takes, on an average, around 6 seconds to complete. The interaction protocol (downloading code and data from the internet) takes around 5 seconds to complete. For this application 9Kb of data was downloaded from the internet using T-Mobil as the service provider. Discovery time dominates and varies from 22.5 seconds to as much as 35 seconds depending on which mechanism was finally effective in discovering the services. This application was tested on Sony Ericsson P900 phones.

The same application can be used in the context of a user dining with her friends in a restaurant. We have implemented an extension of this application that lets the user split the restaurant bill with her friends. The bill migrates between the phones of the friends (selected by the user) and everyone is asked to contribute some amount which is then accepted or rejected by the initiator. The full bill is payed by the initiator but IOU's are maintained on the phones. The bill splitting part as of now does not support any authentication.

3.2 Door Application

Beaufour et al [14] had proposed the idea of opening doors using digital keys. However, they assume that the keys already exist on the phone which limits the usability of the application. We have implemented this application on top of the SDIPP architecture on P900 phones and demonstrated it on the doors of the Computer Science Department.

Our implementation allows the user to download keys from a trusted web server. The user has to be registered with the web server which maintains an access control list and key database for every digital door.

After discovering the doors around him using the discovery protocol, the user's phone downloads the interface and key for opening the door, from the web server. Personal information of the user is piggybacked on the request to the web server. The web server releases the key after authenticating the user on the basis of his personal information. The phone then interacts with the door device by executing the downloaded interface. Key once downloaded can be reused by the user for future use.

We are currently investigating the possibility of phone-based authentication instead of user-based authentication. One possible solution would be to embed the door key inside the executable interface and associate a product key with the interface (as in several Windows based softwares). The IMEI number of the phone could serve as the product key. When the interface loads up on the phone, it would make a system call to retrieve the IMEI number of the phone. Only if the IMEI number of the phone matches the product key of the interface, would the interface execute. This avoids the need of maintaining an access control list based on personal information. An access control list based on IMEI numbers is much more secure and privacy-friendly.

We would like to incorporate the feature of sharing keys with friends, but there are serious security issues associated with it. The ideal solution would be to let the owner of the digital key replicate or derive a key that can be transferred to a friend's phone in such a way that the derived key can neither be tampered with nor replicated by the friend. We do not have a foolproof algorithm for implementing this yet.

We have demonstrated this application on the doors of the Computer Science department. We emulated the Bluetooth enabled door device by a Smart Phone which runs the *Door Open* service. The user's phone only interacts with the *Door Open* service and the web server that stores the keys. The door device communicates with a back end computer that actually controls the doors.

We built our own control circuit driven by the back end computer's serial port that controls the power supply to the door lock. On receiving a signal from the door device, the computer sets the Data Terminal Ready Bit to 1 which switches on a 24V power supply to the door lock thereby opening it. Excluding discovery, the whole procedure takes around 5.5 sec to complete. Since there is no payment involved, the payment protocol is never invoked in this application.

4 Bluetooth Inquiry Clash

We noticed that when two phones are simultaneously in inquiry mode, they become indiscoverable to each other which is due to the fact that, when in inquiry mode the Bluetooth radio bandwidth is completely consumed. When a Bluetooth device is in the inquiry mode, it continuously transmits inquiry packets and hops frequencies 3200 times per second. A device that allows itself to be discovered, regularly enters the inquiry scan state to respond to inquiry messages, hopping frequencies once every 1.28 seconds. In order to discover all devices, the device must spend at least 10.24 seconds in the inquiry mode [11] [9]. Once discovery has completed, the device behaves like other devices, entering the inquiry scan state periodically. When device discovery is followed by service discovery the minimum time to be spent in the inquiry mode is even larger.

We have observed that on an average a P900 phone takes 22.5 seconds to discover all devices and services. Inquiry is a process that inside most basebands takes up all the radio bandwidth and we have observed this to be true for P900 phones. This means that a phone, when in the inquiry mode, cannot use the radio for anything else except actions like *local friendly name retrieval* or *local parameter retrieval*, which implies that the services on the phone become indiscoverable while it is in the discovery mode.

We can envision many applications being deployed in the future where Bluetooth devices continuously try to discover other Bluetooth devices/services around them. In the *Door Application*, for example, the door devices could poll instead of the phones as in [14]. Similarly, in the *Restaurant Application* the restaurant devices might poll in order to push advertisements to the handhelds. Another example is that of the WAP-push based advertising system described in [11].

In order to analyze and demonstrate the effect of this problem we implemented the *Profile Exchange* service. This is an application to discover and retrieve the Profiles/Contact Information stored on other people's Smart Phones. This application was implemented in Java MIDP and tested on P900 phones. In order for a remote profile to be discoverable, the owner of that phone must have the phone in discoverable mode and the Profile Exchange service must be running in the background. The application is helpful in meetings and conferences where people want to know each other and exchange contact information or when a traveler on a train wants to find a *doctor*.

However, this application is effective only when there are many people running the service on their phones, each willing to exchange personal profiles. This implies that all those phones would be simultaneously in the polling mode trying to discover services on other phones, since polling is the only mechanism for discovery. As everyone would like to discover profiles as quickly as possible, the application would exhibit *greedy* behavior. This would result in inquiry clashes as mentioned above.

This problem is similar in nature to that of nodes connected on an ethernet, each trying to send data periodically, but unlike ethernet which is a static system, this is more dynamic in nature as new devices are encountered and old

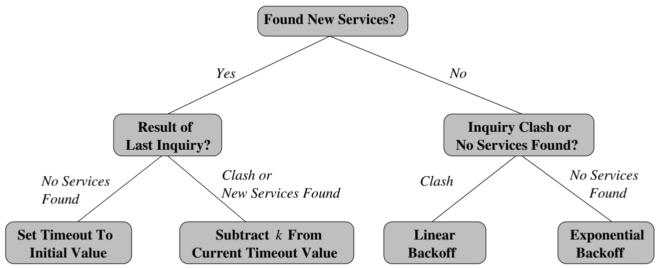

Figure 7. Policy for Timeout

Table 2. Comparing *Random* With Our Policy

Number of Phones	Discovery Completion Time	
	Random	Policy
3	10 min	5 min
4	18 min	12 min

ones disappear due to mobility. The solution to this problem (at the application layer) lies in choosing the optimal timeout value *t* between two consecutive polls. A very small *t* would result in large number of clashes while a very large *t* would result in inefficiency.

If the timeout t is constant, two phones running the same application and hence polling after every t seconds will never be able to discover each other. A better choice would be to choose t randomly between a certain interval $[0, r]$. We call this strategy *Random*. Let c denote the time it takes for discovery to complete, during which time the services on the device become indiscoverable. Every device is discoverable with probability $1 - c/r$.

Let X_i be a random variable denoting the time instant when device i started discovery, $0 \leq X_i \leq r$. The probability p of two devices i and j being able to discover each other in the time interval $[0, r]$ is given by

$$P(\mid X_i - X_j \mid > c) \tag{1}$$

which comes to $(1-c/r)^2$. Let $Y_{ij} (i \neq j, Y_{ij} = Y_{ji})$ denote the number of attempts needed for i and j to discover each other. Y_{ij} follows a geometric probability distribution. Let Y be a random variable denoting the number of attempts after which n devices would have all discovered each other.

$$Y = \sum_{i,\, j>i} Y_{ij} \tag{2}$$

Y follows a negative binomial distribution. Expected value of Y is given by

$$E(Y) = \frac{\binom{n}{2}}{p} \tag{3}$$

where p is $P(\mid X_i - X_j \mid > c) = (1 - c/r)^2$

Let T be the random variable that denotes the time after which n devices would have all discovered each other.

$$T = rY \tag{4}$$

$$E(T) = rE(Y) = \frac{r\binom{n}{2}}{p} \tag{5}$$

In our case c is 22.5 seconds. We chose r to be $2c$ which is 45 seconds, for best results. Substituting the values, we obtain the expected time for $n = 3$ devices to be 9 minutes and for $n = 4$, it is 18 minutes. This matched very well with our experiments. However, this is far away from the ideal, which for 3 devices is $3c$ which is 67.5 seconds (1 minute 7.5 seconds) and for 4 devices, 90 seconds (1 minute 30 seconds). However, the ideal is achievable only with an oracle aware of all devices, that instructs the devices when to start discovery.

After careful analysis and experimentation we came up with a policy for varying t dynamically that seems to do much better than *Random*. The policy was motivated by the backoff algorithms used to minimize clashes in an ethernet. In addition, it also takes into account the dynamic nature of the problem by keeping track of events that happened during the last discovery attempt. The user may suddenly enter a region where there are many new services available in which case he should poll more often, however, if there are no new services found or if a clash happens, then the value of t should be increased. Figure 7 shows the policy. For best results, original(initial) value of timeout t was chosen to be r (45 seconds) and *k* which is a constant, was chosen to be 15 seconds.

Table 2 shows how this policy compares with *Random*. We believe there is room for improvement. Better results could be obtained by using machine learning techniques to learn the policy for varying t.

5 Related Work

Aalto et al [11] describe a system for Bluetooth and WAP Push based advertising for Smart Phones. I-mode [5] makes web service provisioning on Smart Phones easier. UDDI [7] is a web-based distributed directory that enables profit-based web services to list themselves on the internet and discover each other, similar to *yellow pages*. Beaufour et al [14] propose the idea of storing digital keys on

Smart Phones for opening doors. Jini [28] proposes the idea of downloading the published objects for interacting with the service. In an earlier work [20], we had published how Smart Phones can be used to support several ubiquitous computing models. Cooltown [21] and Splendor [31] utilize the idea of associating devices and services with the web. SDIPP goes a step further by utilizing web connectivity on phones for *(1).* augmenting a *service-client* based discovery protocol (Bluetooth SDP) *(2).* dynamically obtaining the protocol to interact with a service and *(3).* paying services in a seamless way. SDIPP also integrates adhoc service discovery using Smart Messages [26] with the web assisted Bluetooth SDP in a cost-sensitive heirarchical way and utilizes personal information, preferences and location information for discovery. SDIPP unifies several ideas to implement an infrastructure-less solution suitable for nomadic computing and has been shown to be effective in many scenarios described in the paper.

6 Discussion

Like other service discovery protocols, SDIPP assumes that services are SDIPP-aware. Using ontologies can be instrumental in decoupling services from access mechanisms. In the current implementation of SDIPP, the interaction between client and service takes place over Bluetooth thereby restricting the scope of SDIPP to Bluetooth services. An ontological service description layer with bindings to different service discovery protocols is one of the many possible ways to approach this problem.

Bluetooth SDP is the first service discovery protocol to be marketed globally along with several Bluetooth products, such as Bluetooth routers. Virtuous as it may be, it is quite well-known that Bluetooth has its own idiosyncrasies, some of which have been pointed out in the paper, such as inquiry clash and instability. We realized that Bluetooth does not perform very well in highly dynamic environments for mainly two reasons: short range and long discovery completion time. Some of these limitations creep into SDIPP which builds on top of Bluetooth SDP.

Limited battery time is the single most important factor that stands in the way of smart phones becoming computing devices. Smart Phones can alleviate the much discussed problem of building economic models around technological solutions that take a SOC (Service Oriented Computing) view. A widely and commonly used service access mechanism with low deployment overheads can be instrumental in convincing industry to manufacture smart devices and service providers to install ubiquitous services.

Context-awareness, privacy and energy efficiency are by far the most important technical challenges facing the pervasive computing community today and in order to provide real solutions it is important to build real infrastructures in which these problems manifest themselves.

7 Conclusions and Future Work

In this paper, we have outlined the design of an infrastructure that provides a real-life solution to the problem of interacting with services in nomadic ubiquitous computing environments, by advocating the use of Smart Phones as clients and exploiting the resources available on phones. In particular, we have sketched a unified protocol, SDIPP, for discovering, accessing and paying services dynamically using Smart Phones. This work is complementary to the work being done in designing service discovery protocols and payment systems for ubiquitous computing, which can be integrated with the framework described in the paper.

We have advocated the use of *dual connectivity* on phones for integrating local services with web services in a secure way. Context and location awareness are integrated into SDIPP. Although personal information is used for authentication, it is shared with only trusted web servers, without compromising significantly on privacy. As mentioned earlier, a more privacy-friendly solution would be phone-based authentication rather than user-based authentication. Using phone IMEI number as product key could be an interesting solution.

We have evaluated our protocol and demonstrated its feasibility through two applications. We pointed out the limitations of Bluetooth on Smart Phones and provided an application level solution for inquiry clash.

There are two major issues that we have not addressed in this paper: security and energy efficiency. Since personal information of the owner is stored on the phone, loosing it could pose a serious security threat to the owner. The data stored on the phone should be made inaccessible to anyone but the phone owner. A simple password scheme is insufficient because entering a password every time confidential data is accessed could be a major turn off for the users. We plan to investigate both software protection mechanisms and hardware solutions (e.g., biometric security using fingerprint or voice recognition).

So far, there is no systematic characterization of energy consumption on Smart Phones. Energy consumption is going to be a deciding factor in the success of Smart Phones.

We have set up an infrastructure for carrying out energy measurements on phones in collaboration with Dr. Ulrich Kremer. Since phones, as of now, are closed platforms, we are looking into source code transformations for energy efficiency. We are currently working on designing compiler based network optimizations that exploit network topology to save on energy spent on establishing connections by using techniques like message aggregation.

A relatively less explored and very promising area of research is the use of phone sensors (e.g camera, microphone) in pervasive computing applications. Processing documents using phone cameras or building speech-based user interfaces on phones is among the many possibilities waiting to be explored.

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