Service discovery in multi-radio networks: an assessment of existing protocols

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ABSTRACT

The wide deployment of mobile networks and the emergence of powerful portable devices has given core to pervasive computing. As particularly addressed by Beyond 3G (B3G) networks, the recent evolution of mobile networks introduces the convergence of wireless technologies, where several radio interfaces are to be used concurrently. Thus, B3G-aware applications shall make the most effective use of this connectivity. In pervasive environments, mobile users may discover and access services offered on the networks using Service Discovery Protocols (SDPs). Several SDPs are currently in use, each one designed for specific target network architecture and setting. Thus, in a multi-radio environment, each SDP does not equally suit each radio interface. In order to provide effective service discovery in multi-radio networks, the most resource efficient interface shall be chosen with respect to two main criteria: the adequacy of the radio interface against the SDP to be used, and energy saving, which is crucial for battery-powered devices. Toward this goal, this paper assesses how to exploit multiple radio interfaces from the standpoint of service discovery and access with respect to energy consumption, and the adequacy of the legacy SDPs with the various networks, so as to classify the most appropriate networks for each SDP.

Categories and Subject Descriptors

C.2.4 [**Computer Systems Organization**]: Computer - Communication Networks—*Distributed Systems*

General Terms

Measurement, Performance

Keywords

Service discovery, B3G networks, energy consumption.

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1. INTRODUCTION

While wireless networking technologies were developed autonomously, and sometimes in direct concurrence with each other, recent evolution of mobile networks outlines a new trend: several radio technologies are to be used concurrently and complementarily. This new trend, called convergence of mobile networks, is more particularly addressed in Beyond 3G (B3G) networks. B3G-capable devices then hold several radio interfaces, and switching from one radio interface to another, e.g., upon disconnection (vertical hand over). Thus, effective deployment of distributed applications over several heterogeneous radio networks appears as a key challenge for distributed systems.

We more specifically focus on the concept of smart spaces [2] surrounded by B3G networks. That is, a user is evolving in an environment where many networked objects (e.g., PCs, PDAs, CE devices, smartphones, sensors) provide services and information via one or more of the available wireless networks. The user further has at its disposal a handheld device with several radio interfaces, and is thus able to move around and access the services offered on all the networks. When services may be accessed via several radio interfaces, B3G-capable applications shall communicate through the most appropriate interface according to criteria such as energy consumption, which is a crucial constraint for embeded devices [10] [4]. Still, in order to be accessed, services must first be discovered. Over the years, many academic and industry supported service discovery protocols (SDPs) have been proposed for specific networks (e.g., Jini [12] for intranets, UPnP [11] for home networks). While efficient for the targeted environment, existing SDPs prove to be inefficient (e.g., communication cost overhead) or not applicable (e.g., filtered multicast) in different network settings. Meanwhile, when an application may use several radio interfaces, the least power consuming interface may not be the most effective choice, if the SDP to be used does not suit the interface's properties and settings.

In the above context, our objective is to support effective service discovery in multi-radio networks so as to offer energy efficient, integrated service discovery. The solution shall exploit the various networks on the mobile, wireless devices, while overcoming SDPs heterogeneity, in a way that both minimizes resource consumption and offers response time comparable to that of legacy SDPs. Towards this goal, this paper assesses the impact of multi-radio networking on service discovery together with the adequacy of existing SDPs. Next section is dedicated to the assessment of

Table 1: Base consumption without radio interface

Interface	Consumption (%)
Without radio interface	7.5

Table 2: Consumption of each radio interface for passive discovery

Interface		Consumption (%)
Wifi	Ad-hoc	5
	Infrastructure	1.5
Bluetooth	Piconet	2.5
	PAN	3

the various radio interfaces in use today with respect to energy consumption for typical services discovery and access scenario. In Section 3, we inspect the bindings between the SDPs features and the multiple radio interfaces in order to sort out incompatibilities and rate the usage efficiency of each SDP on the different radio networks. This study results in a matrix of values rating the adequacy of use of each SDP against each radio interface. Finally, we conclude by a summary of our contribution in Section 4.

2. ASSESSING MULTI-RADIO BASED SERVICE DISCOVERY WITH RESPECT TO ENERGY CONSUMPTION

It is a known fact that all radio interfaces do not consume the same amount of energy during transfer. In particular, several studies of the power consumption of the Bluetooth and Wifi interfaces may be found in the literature [8] [9]. However, all these studies concern measurements done while transferring large files at a sustained rate, whereas SDPs are not based on this type of sustained exchange. SDPs rather use short and cyclic transfers for active discovery, and sniffing for passive discovery.

The goal of this study is to measure the power consumed on handheld devices (namely HP Ipaq HX4700 and HP Ipaq H6340) during active (§ 2.1) and passive (§ 2.2) service discovery, and service access through their radio interfaces (Wifi and Bluetooth). The Wifi and Bluetooth interfaces are further studied according to their various operating modes: the Wifi interface is divided into the ad hoc and infrastructure modes, and the Bluetooth interface in the Bluetooth piconet and Bluetooth NAP modes. We simulate passive discovery by putting the interfaces in a listening state during a defined period of time. Active discovery is simulated by executing several short transfers cyclically. Next, we also measure power consumption during sustained transfers to simulate services access and infer a model of consumption for each interface, in order to compare our measures with the ones that may be found in the literature (§ 2.3). Finally, these results are interpreted and discussed in the framework of energy-efficient service discovery and service access in multi-radio networks (§ 2.4).

In all the tests, we measure the relative power consumption after half an hour of operation. The curves of discharge of the devices not being linear, all measurements are started when the battery is fully loaded. All the measurements are reiterated several times and the mean value is given as final result, as we obtained low coefficient of variation. We first perform a base measurement consisting in letting the Ipaq switched on for half an hour with all the radio interfaces down, in order to be able to discriminate the consumption of the radio interfaces with that of the other peripheral elements. This base result is given in Table 1. Next results are given in percentage of battery consumed in addition to the base measurement.

2.1 Measurements for passive discovery

The first test-bed consists in simulating service discovery following the passive model as with, e.g., UPnP. In this mode, clients never send requests but are continuously listening on the network interface for service advertisements. To simulate this operating mode we force one radio interface at a time in an "always on" state and measure the power consumed after half an hour of listening. In the Wifi ad hoc mode, the device is bound to an existing group. In the Wifi infrastructure mode, the device is associated with an access point and in the Bluetooth PAN Mode it is linked with a network access point. We make sure the device obtains an IP address and is fully network-operational before starting the measurements. The consumption of each radio interface after half an hour of passive discovery is given in Table 2.

For passive discovery, the most consuming radio interface is Wifi in the ad hoc mode with 5% of the battery consumed by the interface after half an hour. This result explains by the amount of signaling messages exchanged between the devices to manage the group, forbidding hardware optimization mechanisms (idle mode) to operate. Signaling being greatly reduced when an access point manages the associations, these optimizations take place in the Wifi infrastructure mode, which is the least consuming interface with only 1.5% of the battery consumed. The Bluetooth interface is commonly known as being more energy efficient than Wifi. This assertion may be verified when comparing the Bluetooth consumption with the measurements in the Wifi ad hoc mode. In its two modes, Bluetooth has a better efficiency with 2.5% of the energy used in the piconet mode and 3% in the PAN mode. Nevertheless, this assertion is no longer true when comparing Bluetooth with Wifi in the infrastructure mode. Indeed, optimizations at the hardware level consisting in putting the interface in an energy saving mode when idled seem to be more efficient on the Wifi interface in the infrastructure mode than on Bluetooth.

As a conclusion, the most energy-efficient medium for passive discovery is the Wifi interface when used in the infrastructure mode. On the other hand, switching this interface to the ad hoc mode renders passive discovery very power consuming and should thus be avoided. When Bluetooth is used for passive discovery, both modes consume almost the same amount of energy.

2.2 Measurements for active discovery

We now measure the energy consumption of the different radio interfaces when used to cyclically perform active discovery in order to maintain knowledge of service offers in the course of time as with, e.g., SLP. We simulate a typical real life scenario where a user carrying a handheld device is walking slowly along a corridor. The device cyclically emits discovery requests in order to discover services offered by the devices in the surrounding. The scenario is depicted in Figure 1. In order to simulate this behavior, request/response sequences are processed cyclically on the device. Further-

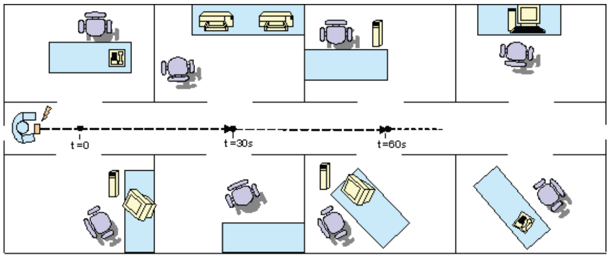


Figure 1: Scenario for active service discovery

Table 3: Consumption of each radio interface for active discovery

Interface		Consumption (%)
Wifi	Ad-hoc	6.5
	Infrastructure	6.5
Bluetooth	Piconet	5.5
	PAN	5.5

more, the volume of data exchanged is in the order of magnitude of the mean volume of data transferred by the leading SDPs (i.e., 1.5 kilo byte). Indeed, request weights 500 bytes and response messages are 1 kilo bytes long. The period between two sequences lasts 30s, which allows effectively taking into account the dynamicity of the service offers in an evolving environment, and also represents for a slowly walking human about 16 meters traveled, which corresponds to the emission range of Bluetooth emitters placed in desks as in, e.g., smart spaces. Like the previous measurements, we let the simulation run for half an hour. Results are given in Table 3.

We may first notice that when small transfers occur periodically, the energy consumption of Wifi and Bluetooth is not influenced by the mode in which they operate. Therefore, even if the volume of data transferred is small, the hardware optimizations in the Wifi infrastructure mode are not able to take place and the measured consumption of the infrastructure mode catches up with the one of the ad hoc mode. Indeed, both modes of the Wifi interface are more consuming than the ones of the Bluetooth interface, with respectively 6.5% and 5.5% of the battery consumed after half an hour. According to these results, active service discovery should be performed via Bluetooth interfaces, in order to optimize energy consumption.

2.3 Measurements for services access with sustained transfers

The aim of the last simulation is twofold: to compare consumption of the network interfaces when accessing services where sustained data flows are exchanged, and to verify that our results are congruent with those found in the literature [1][2]. In this simulation, we make the handheld device exchange large sets of data back and forth, fully filling its bandwidth during half an hour. More precisely, the device sends a 10 MB file, and then receives back a 10 MB file. The cycle reiterates without delay during half an hour. The measured consumption values are reported in Table 4, along with the volume of data transferred on each interface.

After 30 minutes of data exchange at full rate, the Wifi interface has consumed 8.5% of the battery power, the Bluetooth interface in the PAN mode has consumed 5.5% and the piconet mode is the most frugal with a consumption of 4.8%. Nevertheless, when looking at the different volumes of data transferred across each interface, it is clear that these measurements cannot be compared as is. As Bluetooth and Wifi have very different bandwidth capacities, the volume of data exchanged during a defined time lapse is disproportioned: the Wifi ad hoc bandwidth is 5 times larger than the Bluetooth piconet bandwidth. It is thus not fair to compare the interfaces by comparing the measured consumptions at full rate. This is a well known problem in the literature. Work has been undertaken to model the energy consumption of the Bluetooth and Wifi interfaces [1], and also faced the need to define comparison equivalencies with respect to the asymmetrical bandwidths of the radio interfaces. Nevertheless, no well recognized solution has emerged.

Table 4: Power consumption and data transfer.

Interface		Consumption	Volume
Wifi	Ad-hoc	8.5 %	270 MB
	Infrastructure	8.5 %	250 MB
Bluetooth	Piconet	4.8 %	54 MB
	PAN	5.5 %	80 MB

Table 5: Power consumption per 100 megabytes

Interface		Consumption (%/100 MB)
Wifi	Ad-hoc	3.1
	Infrastructure	3.4
Bluetooth	Piconet	8.8
	PAN	6.9

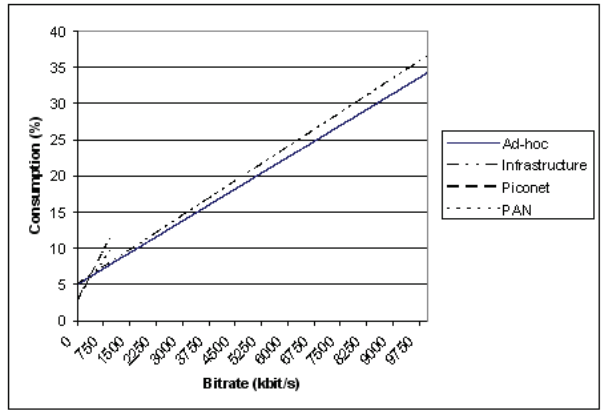
A basic comparison equivalency consists in converting the consumptions of each interface reported in Table 4 into a 100 MB base by applying a golden rule. These values are gathered in Table 5. On the golden rule basis, the cost per megabyte is at least twice lower for the Wifi interface than for Bluetooth. The Wifi interface seems thus much more attractive than Bluetooth for data-intensive applications. Nevertheless, this type of comparison implies that the only source of energy consumption that must be taken into account comes from the emission and reception of packets. The results outlined in the previous section about measurements done after passive discovery show that even when almost no communication occurs on the interfaces, their power consumption is not negligible. We call this value base consumption. Therefore, the energy consumption of an interface is made up of the constant base consumption and of the per-packet consumption relating to the bitrate of the transmission. When comparing the measured consumptions when the interfaces are idle (Table 2) with the measured consumptions at full rate (Table 4), we can see that base consumption represents a large part of the interface's total consumption. Moreover, the golden rule applied on the consumptions at full rate to obtain the power consumptions per 100 MB (Table 5) does not take into account the fact that the global consumption arranges with the base consumption, which is not dependant on the volume of data transmitted. Therefore, in order to refine the approximation operated in Table 5, we must differentiate base consumption and per-packet consumption from the consumptions given in Table 4 before applying the golden rule.

Table 6: Base consumption for each interface

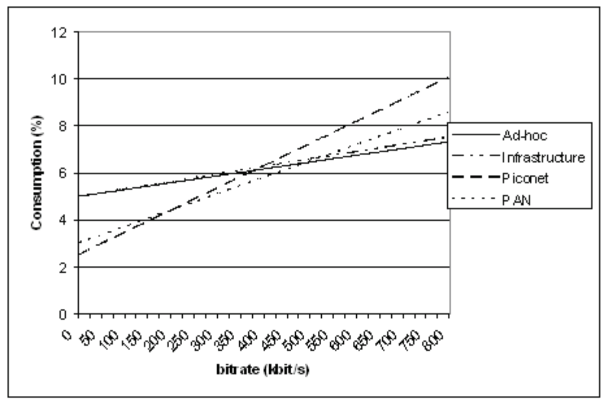
Interface		Consumption (%)
Wifi	Ad-hoc	5
	Infrastructure	5
Bluetooth	Piconet	2.5
	PAN	3

Because of hardware optimizations for energy saving, the values measured in Table 2 cannot be used as is as base consumption values. This is particularly true for the Wifi infrastructure mode, as outlined in Table 3, where even if a small amount of data is transmitted, power consumption increases significantly. The base consumption should be measured by transmitting a sufficient volume of data not to let the radio interfaces idle, in order to overcome hardware optimizations, but small enough to negligibly alter the measured consumption with per-packet consumption. These measurements have been obtained by using the same test bed as the one used in the active discovery simulation, but sending only one ping packet every 30 seconds. A ping packet being 84 bytes long, 5 kilo bytes have been sent after half an hour. This is 18 times smaller than the volume of data exchanged for active discovery, and negligible compared to the amount of data exchanged at full rate. The results of this experiment are given in Table 6. The small amount of data periodically exchanged is sufficient to prevent the use of hardware optimizations, as may be seen with the value measured for the Wifi infrastructure mode. This value increases from 1.5% in Table 2 to 5% in Table 6. The alteration of the consumption of the other interfaces is so negligible that it does not affect the other (rounded) values reported in Table 6. This hints that in this simulation the per-packet consumption is negligible; hence the measured consumptions reported in Table 6 are quite precisely the base consumption values of each interface. Once base consumption is known, we may substract it from the consumption measured at full rate in order to obtain the transmission cost. This remaining value may be correlated with the volume of data transmitted from Table 4 to approximate the per-packet consumption.

Finally, by adding the base consumption value from Table 6 with the estimated per-packet consumption, we obtain the global energy consumption given in Table 7. When 100 MBytes are transmitted in 30 minutes, all the estimated global consumption values lie between 6.1% and 6.7% (Table 7, right most column). When taking into account the error rate due to the approximation of the formula, we can conclude that those values are almost identical. The value chosen for comparison (100 Mbytes/30 min., which converts into 450 kbit/s) is the bitrate around which Wifi becomes more energy efficient than Bluetooth. More precisely, the results gathered in Tables 6 and 7 characterize the consumption models of the radio interfaces. The base consumption values in Table 6 show that the Bluetooth interface, in the two modes, has a lower base consumption than the Wifi interface, while the per-packet consumption values in the second column of the Table 7 show that the energy consumption of Bluetooth increases faster than the one of Wifi, when the transmission rate increases. According to this model, the power consumption of each interface according to the bitrate may be plotted by a line starting at the base consumption value and whose slope is the per-packet cost.



(a) Power consumption of the radio interfaces after 30 min. according to bitrate. Scale : Wifi bandwidth



(b) Power consumption of the radio interfaces zoomed around Bluetooth bandwidth

Figure 2: Power consumption of Bluetooth and Wifi interfaces according to bitrate

The power consumption curves for each radio interface are depicted in Figure 2. Figure 2(a) shows that the Bluetooth interface is more efficient than the Wifi interface for low bitrates, as outlined by the base consumption values. Nevertheless, as the per-packet cost of the two modes of Bluetooth is more important than the ones of the two modes of Wifi, the consumption lines of the Bluetooth interface abruptly increase and thus the power consumption of the Bluetooth interface quickly overtakes the consumption of the Wifi interface. Moreover, the plot of the Bluetooth curves has been stopped at 1 Mbit/s, as this is the theoretical maximal bandwidth of the Bluetooth interface, whereas Wifi curves go much further, as 802.11b's theoretical limit arises at 10 Mbit/s. The same graphic, zoomed around the cross points, may be found in Figure 2(b). Figure 2(b) clearly shows that the Bluetooth interface is only preferable over the Wifi interface for bitrates up to 380 kbits/s in the piconet mode and 520 kbits/s in the PAN mode. For larger bitrates, the Wifi interface is less consuming than the Bluetooth interface. Of course, the Wifi interface also becomes the sole practical solution when the Bluetooth interface cannot cope with the required bandwidth any more.

Table 7: Transmission and global consumptions per 100 MBytes for each interface

Interface		Transmission overhead (%)	Per-packet consumption (%/100MB)	Global consumption (%/100MB)
Wifi	Ad-hoc	3.5	1.3	6.3
	Infrastructure	3.5	1.4	6.4
Bluetooth	Piconet	2.3	4.2	6.7
	PAN	2.5	3.1	6.1

Globally, even if for very small bitrates the Bluetooth interface is less consuming than the Wifi interface, its high per-packet cost quickly renders the Wifi interface more attractive. Therefore, the Wifi interface should be preferred for services access, as the required bandwidth will most of the time be larger than this cross point. Moreover, if while using the Bluetooth interface, the required bitrate increases over time, one may quickly face hardware non feasibility whereas Wifi could sustain a much larger bandwidth.

2.4 Energy-efficient service discovery and access in multi-radio networks

Globally, the most energy efficient operating mode consists in using the Bluetooth interface for discovery, and the Wifi interface for service access. This scenario requires that gateways between the Bluetooth network and the Wifi network be available in the environment, or that all the devices use both interfaces concurrently. These usages are not currently widespread, but are conceivable in specific cases such as enterprise deployment. Nevertheless, such a scheme assumes that every SDP can be used adequately with every radio interface. However, SDPs are designed with a specific networking environment in mind, and thus do not behave the same way on different radio networks. According to its intrinsic specifics, such as its discovery model or networking protocol, a SDP may be technically unusable on a specific radio interface. The next section assesses the features of existing SDPs with respect to the wireless network interfaces composing the multi-radio network in order to rate the adequacy of each SDP against each radio interface.

3. ASSESSING EXISTING SDPS IN B3G NETWORKS ENVIRONMENT

Service Discovery Protocols (SDPs) enable finding and using networked services without any previous knowledge of the services' specific location. To provision exhaustive knowledge of the services offered on the reachable wireless networks, a client may need to use several SDPs, which are not identically suited for every radio interface. Some combinations are even technically unbound. Beyond these incompatibilities, a device may offer connectivity to the same part of the network through two different interfaces. SDPs can thus use one or the other to discover available services. A discovery protocol optimized for multi-radio networking should be able to choose the best suited interface according to the SDP to be used. Therefore, it is crucial to rate the adequacy of each SDP against each radio interface.

The Wifi technology has been designed to operate in two different modes: ad hoc and infrastructure. The infrastructure mode may also be split into a "pure" infrastructure mode (access to the local area network) and a hybrid infrastructure + gateway mode (access to the LAN and beyond). Bluetooth may also be configured into two different operating modes: the "master-slave" piconet mode (the default Bluetooth configuration belongs to this mode), and the IP-based PAN (Personal Area Network) mode. Each of these two modes may also be divided into two. In the piconet mode, a device may provide the "LAN Access" profile, in which case it allows the other devices of the piconet to access the local area network. A node of a PAN can offer the same function, called NAP (Network Access Point). Our analysis thus treats 8 cases of radio interfaces: Wifi infrastructure, Wifi gateway, Wifi ad hoc, Bluetooth piconet, Bluetooth Lan-ap, Bluetooth GN, Bluetooth NAP and GPRS.

Many academic and industry-supported SDPs are available, each with its own features and use case. Among these SDPs, a few ones are more widely deployed and adopted: the second version of IETF's SLP has been standardized in RFC 2608 [7]; UDDI (Universal Description, Discovery, and Integration) [5] is one of the core Web services standards; while Sun Microsystems develops and maintains Jini [12]; and Microsoft bases its strategy on UPnP [11]. In an open environment, these SDPs might be often met and should therefore be studied in the context of multi-radio networking. SLP having two different operating modes/architectures, it is divided into two distinct protocols: SLP with Directory Agent (called SLP with DA) and SLP without DA. Bluetooth being one of the studied radio interfaces, the service discovery protocol defined in the Bluetooth standard (Bluetooth-SDP [1]) is also studied. It is the only SDP that cannot function on IP at all. Finally, even if JXTA [6] is not just a SDP, but rather a set of open protocols that allow any connected device on the network to communicate and collaborate in a P2P manner, its resource discovery needs be studied as it brings different discovery paradigms and possibilities. We also study the lightweight devices version of JXTA, called JXME [3], whose discovery architecture slightly differs from JXTA's : a JXME peer only addresses one single peer (its proxy), which carries out the discovery and forwards the results. Our analysis thus takes into account 8 SDPs: SLP with or without DA, Jini, UDDI, UPnP, Bluetooth SDP, JXTA and JXME.

We first itemize and describe the SDP features that impact upon SDPs' adequacies against the different radio networks (§ 3.1) and outline the relevant properties of the radio interfaces (§ 3.2). We then present our study, which results in a matrix of values rating the adequacy of each SDP against each radio interface. We carry out this analysis by isolating each feature of the SDPs and by checking its adequacy with the relevant properties of each radio interface (§ 3.3). The aggregation of these results concludes this analysis by providing for each SDP a global adequacy against each radio interface, so that a technical incompatibility with only one of the features gives a null value of adequacy (§ 3.4).

3.1 SDP features

The major architectural difference between SDPs concerns the existence of a central repository, and the way service offers are handled. When a central repository exists, the offers are stored and retrieved from this repository, which may possibly be distributed. The architecture is then known as "centralized". When no central repository exists, two cases arise: requests and offers may be directly exchanged from one to all in a peer-to-peer scheme, or discovery is done solely via unicast communications between two devices. In the former scheme, each peer is in charge of caching the received results. We call this architecture peer-to-peer (or P2P). In the latter case, no broadcasting of requests or announcement takes place. Service discovery consists in a single requester directly requesting a specific provider its service offers. Therefore, this architecture is called client/server. SDPs are also aimed at a specific networking environment defined by its size (i.e., small, enterprise or large-size network) and network protocol used. SDPs may or may not allow scalability in terms of number of users and network size. SDPs are further often strongly coupled with some middleware solution forbidding service discovery and access with other middleware.

The features of the studied SDP are characterized in Table 8. It is noticeable that, even if JXTA was designed with the aim of being executed without any dependency on a particular network technology, the porting of the JXTA framework on the Bluetooth stack not being yet operational, the network protocol independence is still theoretical. The SDPs features we have just elicited are the variables rendering the use of each SDP more or less effective with respect to each radio interface. In order to evaluate this level of adequacy, the relevant features of the radio interfaces are discussed in the next section.

3.2 Properties of the radio interfaces

Wireless networks appeared in the late 90s, where each radio technology had been designed for a specific usage. Bluetooth was created with "personal area network" in mind, in order to avoid wires between peripherals, Wifi networks were designed in order to replace wired local area networks, and GPRS technology to offer dial-up wide area network access over the GSM network. In the course of time, these technologies have evolved, providing different possibilities than what they were formerly designed for. Nowadays, radio networks even advertise overlapping usages. This characteristic is addressed by beyond 3G networks, where convergence of radio networks should take place in a way that users becomes unaware of the actual radio technology in use. Nevertheless, radio interfaces still have their own specificities, mostly inherited from their previous usage. Table 9 gathers the specifics of the Wifi, Bluetooth and GPRS interfaces that are of interest in the comparison of SDPs, by modifying their behaviors: network scope (vicinity, local area network or beyond), standard network protocol, bandwidth, and financial cost when their use is not free of charge.

As presented in Table 9, GPRS is the interface that has the least evolved from its originating function, as it still gives access to WAN solely, by using IP. Its bandwidth is still very limited (170 kbit/s) and the user must pay while using it according to the volume of data transferred. The Wifi bandwidth continuously increases, ranging nowadays between 11 and 54 Mbit/s. It uses the IP protocol in all its operating modes. In the ad hoc mode, the device has access to the devices in its vicinity, while in the infrastructure mode the interface gives access to the local area network. In these usages, the communications are free of charge. The addition of a gateway allows Internet access (WAN) in the infrastructure mode, but may render the communications lucrative (case of the hotspots where the user is charged according to time). Bluetooth usage is always free of charge and offers a bandwidth of 1 Mbit/s. In the piconet mode, devices in the vicinity are the only reachable ones, using a particular protocol. If one of these devices offers the LAN access profile, it can be used as a gateway in order to reach the machines on the local area network using IP. Although the piconet mode is the default Bluetooth mode, it is however possible to create an IP network between Bluetooth devices in order to create a "personal area network" (PAN). A Network Access Point (NAP) may reside in the PAN network to thus offer to Bluetooth clients an access to the LAN/WAN.

3.3 Assessing adequacy of SDPs against radio interfaces

In order to obtain a global level of adequacy for each combination of SDP with radio interface, the correlation of the aforementioned SDPs features with radio interfaces properties must be studied. These observations are translated into numerical values, gathered in matrices, one for each SDP feature, where one cell represents the level of adequacy of one SDP against one radio interface with respect to this feature. These matrices are then aggregated in order to provide each SDP with a global level of adequacy against each radio interface, so that a technical incompatibility with only one of the features gives indeed a null value of adequacy.

Table 10 assesses for each SDP its adequacy with the radio networks of interest, according to the type of network and scope assumed for the underlying network. For each pair (protocol, interface) a note of feasibility is given: 2 if the binding is adequate, 1 if operation is possible but imperfect and 0 if it is impossible. JXTA and JXME being designed to function on networks of any size, all the interfaces are adequate. SLP without DA, UPnP and Bluetooth-SDP functioning on small networks, are suited to Wifi in the ad hoc mode and to Bluetooth piconet and PAN. They can also function in a degraded manner on LAN-type networks (Wifi infrastructure, Bluetooth LAN AP and NAP without gateway) but cannot be used on wide-area networks (GPRS, Wifi with gateway). SLP with DA and Jini function perfectly on average sized networks like LAN (Wifi infrastructure, Bluetooth LAN AP and NAP) and can scale if these networks extend (with a gateway). However, they badly function with interfaces offering only WAN access (GPRS). In the same way, it could be possible to use these protocols on proximity interfaces, even if this case is not adequate (Wifi ad hoc, piconet, PAN).

Table 11 assesses the adequacy of SDPs with radio interfaces according to the supported network protocols. All the SDPs are IP-based, except Bluetooth-SDP, which is based on L2CAP. Even if JXTA, JXME and Jini claim network protocol independence, they currently do not have any usable implementations apart from IP-based. Therefore, all the SDPs except Bluetooth-SDP can be used with GPRS and Wifi in all its operating modes, as they offer IP connectivity. Bluetooth in the PAN mode also offers IP connectivity, while in the standard piconet mode it can only use

Table 8: SDPs features

		Architecture			Directory Location	Type of network			Net.		Access mechanism
		Centralized	P2P	Client-Server		small	enterprise	Large	IP	Other	
SLP	with DA	✓			DA(s)		✓	✓	✓		-
	w/o DA		✓		-	✓					
Jini		✓			Lookup Server		✓		✓	✓	Code mobility
UDDI		✓			UDDI directory			✓	✓		-
UPnP			✓		Every devices	✓			✓		SOAP
Bluetooth SDP				✓	-	✓				✓	-
JXTA			✓		Distributed Hash Table on RdV peers of a group	✓	✓	✓	✓	✓	PRP
JXME - proxy			✓	✓		✓	✓	✓	✓	✓	

Table 9: Radio interfaces properties

			Scope			Net. Protocols		Bandwidth	Cost $
			Proximity	LAN	WAN	IP	Other		
Wifi	Infrastucture			✓		✓		11-54 Mbit/s	Free
		gateway		✓	✓				Free or Time based
	Ad-hoc		✓						Free
Bluetooth	piconet		✓				✓ (l2cap)	1 Mbit/s	Free
		LAN Access profile	✓	✓	(✓) gateway	✓ LAN only	✓ proximity		
	PAN	GN	✓			✓	✓		
		NAP	✓	✓	(✓) gateway	✓	✓ proximity		
GPRS					✓	✓		170 kbit/s	Volume

Table 10: SDPs vs. Network scope

		Wifi			Bluetooth				GPRS
		Infrastructure		Ad hoc	piconet		PAN		
			gw			LAN-AP	GN	NAP	
SLP	with DA	2	2	1	1	2	1	2	1
	w/o DA	1	0	2	2	1	2	1	0
Jini		2	2	1	1	2	1	2	1
UDDI		2	2	1	1	2	1	2	1
UPnP		1	0	2	2	1	2	1	0
Bluetooth SDP		0	0	2	2	1	2	1	0
JXTA		2	2	2	2	2	2	2	2
JXME		2	2	2	2	2	2	2	2

Table 11: SDPs vs. Network protocol

		Wifi			Bluetooth				GPRS
		Infrastructure		Ad hoc	piconet		PAN		
			gw			LAN-AP	GN	NAP	
SLP	with DA	2	2	2	0	1	2	2	2
	w/o DA	2	2	2	0	1	2	2	2
Jini		2	2	2	0	1,5	2	2	2
UDDI		2	2	2	0	1	2	2	2
UPnP		2	2	2	0	1	2	2	2
Bluetooth SDP		0	0	0	2	1	2	1	0
JXTA		2	2	2	0,5	1,5	2	2	2
JXME		2	2	2	0,5	1,5	2	2	2

Table 12: SDPs vs. Architecture - refined

		Wifi			Bluetooth				GPRS
		Infrastructure		Ad hoc	piconet		PAN		
			gw			LAN-AP	GN	NAP	
SLP	with DA	2	2	1	1,5	2	1,5	2	2
	w/o DA	2	1	2	1	1,5	1	1,5	1
Jini		2	2	1	1,5	2	1,5	2	2
UDDI		2	2	1	1,5	2	1,5	2	2
UPnP		2	1	2	1	1,5	1	1,5	1
Bluetooth SDP		2	2	2	2	2	2	2	2
JXTA		2	1	2	1	1,5	1	1,5	1
JXME		2	2	1	1,5	2	1,5	2	2

Table 13: SDPs vs. bandwidth usage

		Wifi			Bluetooth				GPRS
		Infrastructure		Ad hoc	piconet		PAN		
			gw			LAN-AP	GN	NAP	
SLP	with DA	1	1	1	1	1	1	1	1
	w/o DA	1	1	1	1	1	1	1	1
Jini		1	1	1	0,75	0,75	0,75	0,75	0,5
UDDI		1	1	1	1	1	1	1	1
UPnP		1	1	1	1	1	1	1	1
Bluetooth SDP		1	1	1	1	1	1	1	1
JXTA		1	1	1	1	1	1	1	1
JXME		1	1	1	1	1	1	1	1

Table 14: Global SDPs / radio interfaces adequacy

		Wifi			Bluetooth				GPRS
		Infrastructure		Ad hoc	piconet		PAN		
			gw			LAN-AP	GN	NAP	
SLP	with DA	8	8	2	0	4	3	8	4
	w/o DA	4	0	8	0	1,5	4	3	0
Jini		8	8	2	0	4,5	2,25	6	2
UDDI		8	8	2	0	4	3	8	4
UPnP		4	0	8	0	1,5	4	3	0
Bluetooth SDP		0	0	0	8	2	8	2	0
JXTA		8	4	8	1	4,5	4	6	4
JXME		8	8	4	1,5	6	6	8	8

Bluetooth-SDP. Finally, when Bluetooth is switched in the LAN-AP mode, L2CAP being used to reach the devices in the vicinity and IP to reach the local area network, all the SDPs can be used even if none makes it possible by itself to traverse the whole set of reachable devices.

As mentioned in § 3.1, we can classify the studied SDPs into three distinct families according to their architecture: central directory based (SLP with DA, Jini, UDDI, JXME), peer-to-peer directory based (SLP w/o DA, UPnP, JXTA) and directory-less (Bluetooth SDP). The architecture of the SDPs, associated with the location of the directory, may be assessed with respect to the topology of the radio network.

The centralized architecture of the SDPs with directory is particularly suited to asymmetrical networks (i.e., all the links of these networks do not share the same characteristics, in particular considering bandwidth limitation) such as GPRS, Wifi infrastructure with gateway, BT-LAN AP and BT-NAP. On these networks, the wireless edge link on the device side typically has a lower bandwidth than the network to which it is inter-connected (GPRS/Internet, Bluetooth/LAN). The centralized architecture limits the volume of communication on this link, as only messages relevant for the client are exchanged between the device and the repository. Moreover, there exists a "logical" optimal location for the directory: on the gateway (offering the LAN-AP service or NAP, on the GPRS proxy or on the Wifi gateway). Operating centralized SDPs on peer-to-peer type networks (Wifi ad hoc, BT piconet, BT GN) is possible but less suitable. There is indeed no logical location for the directory, since by definition all peers are equal and no device should have a particular role. Bluetooth SDP, which belongs to the client/server family, is a case apart since this protocol neither stores the offers in a directory nor performs peer-to-peer exchanges of the advertisements. The only authorized discovery is done by unicast communication between one client and one provider. This simplistic discovery model, particularly suited to the mode of communication used by Bluetooth, does not induce nor is based on any architecture or particular network topology. The only need is that the two devices can reach each other. This protocol is thus appropriate to all the cases. Finally, the Wifi interface in the infrastructure mode is also apart. At first sight, the infrastructure type architecture seems asymmetrical, since an access point acts as a gateway between wired and wireless networks. Thus, SDPs with centralized directory find there a logical location. Nevertheless, nowadays, the characteristics of the wired and Wifi wireless networks are generally rather close. Moreover, the aim of this operating mode is to combine wireless sub-networks with the local area network. From this point of view, the network appearing homogeneous, SDPs with peer-to-peer directory find there a logical operation land. The Wifi infrastructure interface is thus adapted, from the architectural point of view, to both centralized and peer-to-peer SDPs.

Meanwhile, it is necessary to refine the former assessment by also taking into account the broadcasting models and protocols of the SDPs and radio interfaces. If a packet emitted on an ad hoc Wifi network is inevitably received by all the other devices in range, the Bluetooth standards only allow one-to-one communications. Therefore, a "one-to-all" communication must be simulated by several successive unicast transmissions, multiplying the cost of communication. This reveals that directory-less SDPs are better suited to ad hoc Wifi networks, while directory-base SDPs are preferable for the Bluetooth "proximity" scope (piconet and GN). In the case of Bluetooth LAN-AP and NAP, multicast and broadcast cannot be realized between Bluetooth devices, but can be initiated between the gateway and its connected networks. Table 12 presents the refined assessments with respect to the broadcasting models.

Bandwidth is not a de facto discriminating factor in the field of services discovery, as discovery only requires low bandwidth. Bandwidth may however be determinant for service access. All the protocols do not propose a particular access mechanism, and thus cannot be compared on this point. Nevertheless, a particular case arises: Jini. Indeed, as Jini replies to discovery requests by using a code mobility mechanism, service discovery may become expensive in terms of volume of data to be transferred. Jini is thus not indicated when the user has to pay according to the volume of data transferred (GPRS) or when the bandwidth is restricted (GPRS, to a lesser extent Bluetooth). Therefore, the bandwidth factor does not exactly represent the adequacy according to access mechanism. Its aim is rather to operate a decrease in the global rating reflecting the preceding remarks. Table 13 reflects this observation, as default adequacy values according to bandwidth are set to 1, and a small decrease is operated for Jini against GPRS and Bluetooth values.

3.4 Matching SDPs against radio interfaces

In order to obtain a global quantitative rating, providing for each SDP its adequacy against each radio interface, we aggregate all the adequacy values from Tables 10 to 13 by operating the scalar product of these matrices, so that a technical incompatibility with only one of the features gives indeed a null value of adequacy. We thus obtain a matrix of global adequacy represented in Table 14. Each value indicates the level of suitability between a SDP and a radio interface. The higher the value is, the more relevant the use is. The pairs evaluated with the maximum rating (maximum is 8) have a perfect adequacy and should be privileged when their use is possible. Finally, the intermediate values greater than 0 indicate that the use is technically possible, although not being perfectly appropriate.

On the 64 (SDP, radio interface) pairs, 18 obtain the maximal adequacy value and 13 are totally incompatible. The SDP obtaining the best average adequacy is JXME, since it has a perfect adequacy with half of the interfaces. Its operating mode being based on JXTA with added optimizations for embedded devices, it supersedes this one in the context of this study. JXTA logically ranks in second position. JXTA and JXME are the only two SDPs that do not present incompatibility with any radio interface at all. Among the other SDPs, SLP with DA obtains the best adequacy rating, but is incompatible with Bluetooth in the piconet mode. Bluetooth-SDP is logically found as the least adequate, since it is not IP-based and is thus incompatible with the Wifi and GPRS interfaces. It is nonetheless notable that if SLP obtains a very good adequacy when used in the directory mode, this protocol used without directory decreases its rank to penultimate, with the same rating as UPnP.

The SDPs adequacy against radio interfaces matrix characterized in Table 14 may also be read the other way round, in order to estimate the adequacy of the radio interfaces when they are to be used with several SDPs. The interface having at the same time the strongest global adequacy and the largest count of maximal adequacy cases is Wifi in the infrastructure mode. It is closely followed by Bluetooth NAP, which has less SDPs with perfect adequacy (3 against 5) but more homogeneous results: on this interface, no SDP is rated with a null adequacy. Bluetooth piconet has at the same time the worst average adequacy and the greatest number of total incompatibility. It is followed by GPRS for which 3 SDPs are incompatible, and only one SDP (JXME) offers a perfect adequacy. When taking into account the physical radio interface by combining the operating modes, Wifi is the interface with the greatest number of perfect adequacy cases. This interface is thus the least expensive to carry out discovery with a large set of SDPs. However, we can also notice that Wifi does not authorize discovery with Bluetooth-SDP at all. From this point of view, Bluetooth is the only radio interface that allows discovery with all the SDPs, since 3 out of its 4 architectures are compatible with the full set of SDPs, even if the adequacy is not perfect. However, the default Bluetooth architecture (piconet) is the interface with the greatest number of incompatibilities since only Bluetooth SDP and JXME (with a weak adequacy for the latter) functions. Moreover, piconet is the default Bluetooth mode and switching the Bluetooth interface to one of the 3 other modes rather depends on the availability and capabilities of the other devices in the vicinity than on the client device itself.

4. CONCLUSIONS

B3G networks combine multiple wireless networking technologies in order to benefit from their respective advantages and specificities. The increase in computing and communication capacities of portable devices, as well as their mass marketing, allows envisaging the widespread deployment of multi-networks pervasive environments. The emergence of such ambient networks opens new challenges and issues in the development and deployment of distributed systems. A user having a multi-radio capable device benefits from such an ambient network by increasing the perimeter of reachable service providers, at the expense of a higher network management complexity. This complexity, induced by the heterogeneity of the wireless technologies, should be hidden to the user and, to be effective, to the application (e.g., by a middleware solution). In a pervasive environment, services must first be discovered using SDPs. Several SDPs are currently in use, and each one has been designed with specific target network architecture and mode of operation. This leads to another important heterogeneity which must be taken into account. This paper presents two studies needed for multi-radio service discovery in order to exploit the various networks while overcoming SDPs heterogeneity. These two studies assess the two main criterias to be taken into account in order to optimize multi-radio service discovery: energy saving, which is a major issue for battery-powered devices, and the adequacy of SDPs against multi-radio networks. To the best of our knowledge, no other work about energy consumption of radio interfaces has taken into account the specific case of service discovery, and SDPs have never been assessed with multi-radio networking in mind.

Our first study, which measures the power consumption of wireless interfaces during service discovery and access, has shown that the most appropriate case would consist in discovering services via the Bluetooth interface, and access them via the Wifi interface. Meanwhile, this perfect case is not always feasable as: (i) both connectivities are not always available, (ii) when they exist, they do not always reach the same networks and devices, (iii) most of the SDPs have been designed with one networking technology or architecture in mind and may thus be so inefficient when operated on another radio interface that the most efficient solution would be to use another more energy consuming radio interface. Thus, the second study takes into account the specificities of the main SDPs and discussed how they behave when operated on each wireless interface. In order to transpose these qualitative observations into parameters usable by an adaptive algorithm, we inferred quantitative values reflecting the adequacy of use of each SDP against each radio interface.

We are currently using the results of these two studies for the development of a middleware solution for embedded devices. This middleware integrates an adaptive service discovery, which effectively exploits the various networks and SDPs found in the pervasive environment, while hiding the network complexity. It continuously provisions services and stores a list of the retrieved offers on the client in order to minimize the response time of the client's discovery requests, and also takes care of updating the local knowledge over time to reflect the dynamicity in the services offer.

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