Enabling Pervasive Computing with Smart Phones

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The technical and market success of mobile telephony in Europe in the early 90s created considerable interest within the research community on mobile systems. Cellular mobile telephony in particular was established as the technical basis for work investigating appropriate architectures for the provision of information services to mobile users. As a consequence, between 1998 and 2002 the EU Information Society Technology research programme was dominated by the desire to discover the "killer application" for the third generation (3G) of mobile telephony, and thus replicate the success of the second generation. Dozens of projects were initiated to pursue this aim and the authors of this article were intimately involved in several of them. In this retrospective we report of the lessons learnt during our involvement in this research area and we attempt to propose ways in which pervasive computing may benefit from this experience.

A common thread throughout this work is the desire to develop universal information services delivered over ubiquitous, high-speed wireless networks. While the second generation of mobile computing is largely a person-to-person voice (and increasingly short messaging) communications medium, visions for 3G mostly involve the development of data services and corresponding infrastructures to support service provision. Nevertheless, 3G did not arrive when expected but instead the situation today is more heterogeneous with mixed 2G, 2.5G and 3G networks operating side by side with a number of local wireless networking systems, notably based on Wi-Fi and Bluetooth protocols. For this reason, the focus of research has shifted into what is currently known as 4th generation (4G) or Beyond 3G (B3G) mobile networks that are seen to evolve as an extension of the current situation. In many ways, the current assumptions of the European Information Society Technology research programme (running until 2006) are not dissimilar to those proposed in the US as ubiquitous or pervasive computing. However, there are considerable differences for example, regarding the more appropriate development path towards such infrastructures.

An additional driver for this shift in programme priorities is the realisation that miniaturisation of sensing and computational devices allows for deeply embedded wirelessly networked systems. As a result, the vision of the European Information Society Technology programme has been recently updated to the so-called Ambient Intelligence vision [16]. Ambient Intelligence is roughly equivalent to pervasive or ubiquitous computing although arguably it gives priority to specific aspects of such systems, namely to the autonomic learning capability of the system infrastructure itself and also to the design of user interaction mechanisms that cater for individuals and groups in particular social contexts. To be sure, its ultimate aim is a situation where smart artefacts populate the environment and information services are available everywhere to access.

Development of information services for mobile telephones shares several of the challenges of ubiquitous computing: the very small form factor makes user interaction hard, devices may operate in an environment that may not be secure or may even be hostile and last but not least, in addition to network connectivity there is a clear need for infrastructures that support service delivery. Some of the techniques useful for the delivery of services on the small form factor of mobile telephones or PDA-type smart-phones currently available should also be useful for similar devices often used in pervasive systems. It is also worth noting that the use of voice as the interaction modality is rather extensively explored in work on the provision of mobile information services (a review of methods and results can be found in [13]). Further, the fact that a person frequently carries mobile telephones offers distinct opportunities for profile and activity data harvesting as well as for the timely delivery of information services to individuals. Finally, a significant proportion of mobile telephones currently feature wireless local networking capabilities that allow them to interact with other devices in their immediate environment.

One of the most important differences between pervasive computing and mobile telephony systems is the primary network environment they operate in [2]. While most pervasive systems are seen to inherit the legacy of the Internet of open standards and systems and end-to-end application architectures, mobile telephones operate within the confines imposed by the telephony network. Although this may be a more restricted environment it also offers distinct security advantages due to the control and management operations carried out by the network operator. Arguably the most important aspect of this control is the clear separation of the data transfer and control planes in telephony networks that potentially lead to fundamentally different service architectures.

In the remainder of this article we discuss the different ways in which mobile telephones can assist in the development of ubiquitous computing systems: as end-points to mobile information services; as control devices for ubiquitous systems management and configuration; as networking hubs for personal and body area networks and last but not least as identification tokens. We conclude with a discussion of business and practical issues that play a significant role in the deployment of research systems in a realistic situation.

Mobile telephones as information service end-points

Perhaps the most interesting use of a mobile telephone from the perspective of pervasive computing is as the end-point of an information utility or service. Indeed, the ubiquitous delivery of information is one of the most often discussed scenarios of pervasive systems: spatial navigational assistance and recommendation of nearby places of interest, shopping, entertainment, task-specific cognitive assistance, access to personal messaging and schedule information, and healthcare monitoring and diagnosis, are all popular scenarios discussed regularly in the literature. The vision of pervasive computing dictates that such services should be accessible from any location and at any time as needed, also via a variety of artefacts augmented with computational and communications capability. Several types of artefacts supporting this mode of interaction have been discussed in the literature, ranging from ambient displays to tangible interfaces and more traditional appliances. Despite their considerable advantages, such devices are available today in very limited numbers and at very high cost. Instead, mobile telephones offer a short-term solution readily available to a large part of the global population at relatively low cost. Moreover, their current computational capabilities compare favourably with the requirements of several types of applications as well as against several types of devices often used in pervasive computing. Last but not least, mobile cellular telephone networks provide today an almost global ubiquitous wireless access network, which satisfies a significant proportion of the requirements of pervasive computing information service delivery.

The advanced processing capabilities of mobile telephones offer a plethora of opportunities for the development of novel information services. Although some of these services can be delivered via a voice interface, a more interesting situation arises through the use of smart phones to support advanced interactive user interfaces. Indeed, several of the projects we have been involved with aimed to develop such services:

- *mXpress* [4] exploits location sensing and tracking to provide navigational assistance within a trade exhibition space. The system allows pre-registered users who have provided personal profiles to receive targeted content, for example notifications for specific events of interest (http://mexpress.intranet.gr).
- *MyGrocer* [7] is a second-generation pervasive retail system, which includes a shopping list management and order placement client for smart phones (http://www.eltrun.aueb.gr/mygrocer).
- *E-Care* [8] developed a data harvesting system to collect patient vital measurements and provide a care-in-the-community monitoring and alerting service for persons with chronic conditions (http://www.e-care-ist.net/).
- *Tellmaris* [1] employed location sensing to display three-dimensional models of the user locality, overlaid with tourist information (http://www.tellmaris.com/).

A common thread that runs across all four projects is the need to provide contextualized information. In this case, context refers to both the cognitive context of the user and the operational context of the system for example, the wireless bandwidth available. Personal context is particularly critical as it is necessary to minimise the number of steps required to carry out a specific action and thus content and application functionality adaptation is required [14]. Unlike desktop systems where functionality often takes precedence over speed, the small form factor of mobile devices and the limited input device facility (mostly a numeric keypad and in a few cases an Accupoint or a pointing stick) means that users are less likely to complete a task when it requires a long interaction sequence. Extracting common patterns from demographic and historical usage data, which are then used to anticipate user actions or better meet user information requirements, is the more common way to develop models of personal context.

Figure 1. Project Tellmaris employed location sensing to display three-dimensional models of the user locality overlaid with tourist information. This figure shows the client application interface which allows users to navigate the model and discover landmarks and services while visiting the site.

The success rate of user choice prediction can be further improved when their current situation is also considered. For example, location and time of day information can be used to identify specific user activities and roles and thus faster access to specific content or help configure appropriate application functionality. However, such mechanisms can be inaccurate and should be used conservatively and in addition, rather than as an alternative, to other system features that provide assistance in performing tasks efficiently. Indeed, a common pitfall is to optimise aggressively for user interaction: when the wrong pathway is predicted or even worse, when the user is prevented from accessing the required functionality because this does not appear to be a probable alternative, then it is more likely that the user rejects the system than the case where the user only had to deal with the difficulty of navigating the interface [14]. Finally, services can also be adapted to meet system capabilities, primarily in terms of user interface features and available network bandwidth. For example, it is critical for the user experience that a system avoids delivery of rich content developed for a 3G network over a slower network segment which supports only GPRS, as performance is unlikely to be adequate.

Figure 2. MyGrocer used RFID technology to tag supermarket objects and monitor consumption patterns. One of the client applications developed for smart phones involves shopping list management and order placement while on the move.

Over the past few years, the priorities in personalising mobile information services have shifted considerably. The original stated goal was to make information services available to *anyone, anywhere and at any time*, but in practice this aim has been often interpreted as providing everyone, everywhere, all available information all the time and thus, to cognitive overload and services to fail. For example, in project mXpress it was relatively easy to make massive amounts of information available[1] to exhibition visitors but less easy for the users to make sense of this information without appropriate means to organise and track data [giaglis].

Today, the focus of personalisation is on creating information services that deliver the right Information at the right time, in the right place, in the right way, to the right person. To be sure, in a world saturated with mobile information services the competition is not for the distribution of massive amounts of information but rather for the attention of the user. Indeed, early attempts to develop information services for mobile telephones were based on the premise that mobile users are little more than “mobile Internet” users and thus services aimed to reproduce the experience of the Internet browser on a desktop computer, albeit with a more compact interface and less demanding data transfer requirements. This view has been proven to be clearly erroneous and today has very limited use. Instead, mobile information services must be designed specifically for the context of their use. For example, web navigation highlights very well the difference between the desktop and mobile devices. In the first case, it is possible for users to employ a search engine to retrieve relevant results over several pages and then review them in turn, moving from site to site over extended periods of time. This is hardly feasible on a mobile device. Instead, users should be taken directly to a specific location to carry out a short, focused task [15]. Indeed, there is no escaping the fact that information services on the move play a fundamentally different role and cannot be developed

[1] A solution to this problem was introduced based on the trail primitive first introduced by Vannevar Bush in his original article about hypertext, as an information navigation approach.

just by trivially extending the desktop paradigm. Instead, information services have to be designed specifically to match the quick and brief sessions of mobile users.

This application layer property extends beyond the user interface and the application functionality to the architecture of the service itself. The requirements of browsing web pages on a mobile telephone go well beyond the need to display content in a condensed form. In fact, it is necessary that the content itself must be modified to meet user expectations and needs, and more importantly to match user activities. For example, the British Museum maintains Compass, an extensive on-line database with information about objects it holds in its collections. As we have found in a recent study, the information contained in these pages does not meet the needs of mobile users accessing this content during a museum visit. Compass pages often provide lengthy background discussions of objects and exhibitions that require the user to switch from the context of the visit[2] to the context of information browsing with the device. This attracts attention away from the main focus of the experience in a fairly disruptive way. More often, the mobile user requires a concise overview of the object and the relevant page should be written with this aim and possibly in a less academic, more informal style better suited to the discoursive style the visit, rather than the style of a reference guide or an encyclopaedia. While automated summarisation techniques may offer some help in this more often than not, content for the mobile user should be authored or edited by a person to achieve the desired effect. Project Tellmaris highlighted the fact that tourist visits are dominated by the location itinerary. In this case, a complex information service interferes with the actual experience and thus, it is not desirable. Instead, a simple but authoritative response to a location specific query or a notification of change in environmental conditions is seen as more appropriate [1].

The fact that content must be authored specifically for the activity of the mobile user implies that transcoding architectures developed in a variety of mobile computing projects are less important than initially thought. Although this functionality is clearly feasible and in fact is now readily available in commercial platforms, it addresses a problem that has minor implications for the success of a system. Of course, achieving interoperability between devices of the same form factor is clearly desirable and should be accommodated whenever possible. Yet, this finding may have some implications for the design of some emerging pervasive computing infrastructures. Content authored for a smart phone may be inappropriate for users that interact with tangible interfaces or proactive displays and thus design principles developed in the context of mobile telephones may not transfer well to these situations.

Mobile telephones for control of pervasive computing environments

A core ingredient of pervasive computing is the seamless inter-operation of a plethora of devices and electronically augmented artefacts within spaces saturated with wireless communications capability. Looking closer at the home environment for example, one can easily envision a situation where hundreds of (mass

[2] In addition to the physical context, museum visits often have a strong social aspect as visitors mostly go in groups, for example families or school groups.

produced) objects and devices must be configured and managed to operate in a way that satisfies the needs of the family who occupies this space. Although the pervasive computing vision dictates that such devices should be able to adapt autonomically, current techniques cannot support this mode of operation at this scale in a robust and consistent way. A potential solution could be offered by employing the mobile telephone as a control device, in a way similar to the remote control devices most often used in consumer electronics [12].

To be sure, there are several challenges facing this approach, not least the limited availability of standards that are clearly essential for its success. Yet, the concept has certain appeal in that the mobile telephone fits rather well this role. Without a doubt, the processing capability of smart mobile phones allow for flexible functionality that can be adapted or extended to include control functions for particular devices or artefacts. Also, larger form factor smart phones allow for the provision of more intuitive user interfaces. For example, a physical space abstraction can be employed to control multiple devices simultaneously or interpret higher-level commands to device level management functions. Instructions can be transferred locally using a wireless interface. In fact, although infrared communication is relatively low bandwidth and is often discounted in pervasive computing systems in favour of higher power access media we have often found that it is very well suited to this role and could provide an appropriate solution [marsh]. Naturally, a mobile device also offers the opportunity to manage the home environment remotely, for example via a control applet that connects directly to an Open Services Gateway home server [6].

There is another more subtle advantage in the use on the mobile as a remote control in a pervasive computing situation. As we have discovered [11] that users of ubiquitous computing systems have difficulty conceptualising the system and thus developing mental representations and appropriate strategies for interacting with it. The problem is that system functionality is transparent and unlike other computing situations there is no specific point of interaction with the system. Indeed, individuals are used at interacting with information systems via specific service end-points, for example a personal computer, a bank teller machine, a digital television or a mobile phone. Yet, according to Mark Weiser, ubiquitous computing is “invisible, everywhere computing that does not live on a personal device of any sort, but is in the woodwork everywhere” and thus has no specific physical expression[3]. When used to provide the point of contact the mobile telephone becomes a manifestation of the pervasive service and thus much easier to conceptualise and interact with.

Mobile telephones as pervasive network hubs

A more interesting use of mobile telephones in pervasive computing arises when considering its functionality rather than its form. Indeed, a mobile telephone can also be considered as a purely communications device which can offer wide area networking capabilities. It can thus be used as the core hub of a personal or body area network: the cellular telephone interface offers connectivity to remote services and the Internet and the local area network, offers connectivity with local devices.

[3] Where complaints should be addressed when things go wrong!

One incarnation of this concept has been explored in the Healthcare Compunetics architecture [17]: Data harvested from a variety of sensors is processed into an appropriate XML-based specification called *i*-notes, stored for future use and following a predefined policy may be communicated to the appropriate consultant for analysis. Since connectivity with healthcare systems may not always be available, Healthcare Compunetics provides two devices that work together to offer secure storage and seamless communication within a body area network. The first component is the *i*-wand, a wearable storage and processing device with fingerprint authentication. Personal data stored on it are structured in *i*-note format, are checked on the fly for evidence of critical conditions locally and encrypted. The device employs wizards that detect the type of sensor transmitting data, currently supporting a variety of homecare monitors, flat-padded water resistant hypoallergenic dermal patches, and certain biocompatible sensor chips in ingestible capsules. The Mobiliser is a GSM modem core that attached to the *i*-wand and provides communication with back end servers over the cellular network. The combination of these two devices transforms the mobile telephone into the enabler for the provision of the typical ubiquitous information services but having removed the recognisable form of the telephone device itself.

This approach removes the limitations of the mobile telephone form factor and taken to its extreme it implies that the whole personal area network may be viewed as an extended telephone. This view suggests a number of ways that the mobile telephone resembles the usual pervasive computing devices. For example, the Phone Glove project [5] at Ericcson Research Labs introduces the idea of the so-called fragmentised telephone. It consists of a basic communications core embedded in user clothing with the remaining components that usually make up a telephone in its most recognisable form are fragmented and located closer to the point of their actual use. The most common implication of this approach is the use of an earphone instead of a mobile telephone speaker, a common mobile telephone accessory today. A more interesting consequence of this model is the use of electrical field sensing and the so-called finger-joint gesture keypad input paradigm to replace the function of a traditional telephone numeric pad. In the case of the Phone Glove project, the system utilizes the 12 finger phalanges as telephone keypad keys and the thumb as operator.

A similar approach has been used to provide wide area connectivity for a number of projects involving the use of wearables. In some cases, the telephone core is used to transmit data harvested from associated sensors in the body area network and in other cases, the device plays the role of a network router that receives information services from a remote location and passes on the content for further processing or display at another network component. An additional advantage of this approach is that by accessing remote services and the Internet it becomes practical to employ network-based authentication and authorisation processes and thus partially address the problem of secure operation and privacy protection inherent in all pervasive computing environments. In fact, smart phone cores are often seen as the basis for the development of a networking model for ubiquitous computing based on the concept of concentric spheres centred on the user, for example the Multi-sphere Reference Model [3] currently explored within the Wireless World Research Forum.

Mobile telephones as identification tokens

Arguably, one of the most pressing challenges in pervasive computing is security and privacy protection [11]. In many cases mobile telephones can be used to considerably improve this situation by employing the concept of the so-called *secure personal device* whereby the device stores information that can be used to verify the users identity and can make decisions on when to disclose this information. This is a generalisation of a function that all mobile telephones carry out under normal circumstances for example on a GSM network they use their embedded unique identification code and the GSM family of cryptographic algorithms to identify the user to the network and verify its right to access resources and services. The mobile telephone may store additional credentials associated with specific information services, for example electronic commerce account logins and payment information using the Electronic Commerce Modelling Language currently supported by several mobile telephone manufacturers [10]. These credentials are used to authenticate either with remote services over the cellular network or over the local network by directly interacting with the payment facility, for example using the Bluetooth protocol or radio frequency identification tags. NTT DoCoMo has recently introduced the latter option as a commercially available system in Japan under the FeLiCa brand.

Yet, there are more aspects to user identification mobility [10]: identity is mobile between devices, between locations and between roles and contexts. Although mobile telephones can support some of these modes they are less effective with others. For example, a problem closely related to location mobility is that of coordination of authority domains, since a person moving from location-to-location is also usually moving between areas controlled by different organisations. When employees access information systems from their desk both the access medium and the information storage are physically located within a single authority domain regulated by their employer whereas, when they access information via one of their trading partner's extranet, they cross organisational boundaries and the trust relationship between the two organisations must be negotiated as well.

Clearly smart phones can only provide a partial solution to this problem. Mobility between roles and contexts is even harder to address and it is unlikely that a mobile telephone can provide either the computational power or the storage resources to maintain an appropriate representation of roles and predict appropriate actions independently. Of course, the three modes of mobility are not isolated but more often than not, different modes are concurrently modified and thus create much more complex situations than what implied from a single mode in isolation. Finally, another complication that limits the effectiveness of a mobile as the holder of identification credentials is that individual elements that make up the mobile identity may not be stored at the same location but they may be distributed between different locations, authority domains and devices often as a result of regulatory or business reasons.

Business and practical implications

One aspect that clearly differentiates the use of a mobile phone from the use of an open system like the Internet is that in the first case transfer of data is completely controlled by the network provider. Unlike the Internet where data flows mostly freely and without intermediaries (at the application layer), in cellular networks operators fully control every data flow on their network. This has as much to do with historical reasons, since mobile operators have mostly evolved from fixed telephone network operators and follow similar models and strategies, as with the expectations of the users of the two systems. Mobile phone users primarily carry out voice communications and their expectations are shaped by their experiences with fixed telephony. The total control of the medium by operators clearly characterizes which parties may offer services over particular networks and under which circumstances. Naturally it is often the case that the ability to offer a service will involve a profit sharing agreement with the operator.

There is thus a clear question to consider regarding the types of services that can become available if the dominant network access model of pervasive computing is that of the current cellular mobile networks. Indeed, the often-cited success story of the i-mode is clearly based on the ability of the operator to share in the profits of third party providers who are given access to the service. Compare this against the relationship of Internet users with their service providers who have very limited or no control over the user choice of consumed services. Moreover, the current situation is that to a significant proportion of operators, including several involved in 3G, do not see information services as critical for their revenue development. In our work, we have often been restricted by operators that limit movement of data on their networks in favour of voice. For example our recent experience is that one of the major European operators limits the bandwidth available to GPRS users to well below the limit of the technology, often to a few kilobits. Even more characteristically the first 3G operator in the UK completely prevents users accessing information services and actively promotes a business model where growth is based on video messaging. Last but not least, and despite the rapid proliferation of Wi-Fi networks, the majority of European operators claim no to be able to support a profitable business model based on this technology and see it as merely a value added service for business customers rather than a viable public access alternative.

The mobile telephony experience to date has significant lessons to offer in terms of market development of supporting service infrastructures. Indeed, the seamless interoperation envisioned by pervasive computing may well be feasible technically but may not happen due to the lack of successful business models that can support the development of the necessary infrastructure. Yet, one can argue that this is only one of the teething problems of a wireless communications industry that does not fully appreciate the opportunities offered by pervasive computing.

Another lesson that we learnt in our work is that it is much faster to move from one technology generation to the next than it is for individuals and groups to adjust their habits and behaviours so that new technology becomes part of everyday life. This is even more so in the case of mobile telephony as compared to the development of the desktop or the server computer. While previous computing generations used technology to carry out tasks related to primarily professional activities, mobile telephony is a more personal and intimate computing situation. As we have discovered consistently across our work, a mobile telephone is a truly personal device, which is often seen as part of an individual's identity [10]. For this reason, it is much harder to demand that a user adopts specific behaviours to operate the technology (as is the case for desktop office productivity systems) and thus it is the technology itself that must be adapted to meet the needs of individuals and their perceptions of themselves. This pressure to develop calm technology can only become stronger with the introduction of the different pervasive computing technologies that become part of the everyday life and indeed invade the personal space of the users and their intimate activities.

One particularly important consequence is the need to build from their early stages ubiquitous computing system that protects the user context. Indeed, it seems that retrofit trust in any technology is considerably harder to do, especially when it has already been perceived as invasive, intrusive or dangerous. In particular, the rules of ownership and compensation for data created by user actions, which are a core requirement for the provision of context-aware services, must be seen as fair and clearly stated beforehand. Lack of a clear framework to protect private functions or compensate for the use of personal data is seen as clearly unfair and creates negative perceptions of a service. Developing a substrate for the provision of universal services is one of the core challenges for pervasive computing as systems must cater for the national, cultural and religious differences which may often result into system incompatibilities or indeed in the failure of such infrastructures to provide the required adaptation. As we have found in our work [roussos03c] even within a region with relative uniform legislation (the EU) different countries might interpret common rules in incompatible ways or in ways that clearly prevent the processing of personal data in a way that is suitable for the provision of context aware services [9].

Conclusions

Over a period of almost ten years we have been involved in work aiming to make mobile information services practical. Over time our understanding of the types of services that are useful to mobile users has shifted considerably. We anticipate that rather than a single or a small number of services, the greatest benefit for the mobile user will be in connectivity itself that is, being always connect to activities, people and groups that play a central role in everyday life. Interaction with services will not be in long continuous segments which are best facilitated by larger form factor computing devices but rather in short and targeted interactions that fulfil a specific need. Until the delivery of fully practical ubiquitous interfaces and services that would allow for a greater wealth of interactions the smart phone will remain the best available personal computing device.

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