Pervasive computing: Past, present and future

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Stan A Kurkovsky
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Pervasive Computing: Past, Present and Future

Stan Kurkovsky, *Member, IEEE*

Abstract—The paradigm of pervasive computing describes ubiquitous computing environments that provide anytime and anywhere access to information services while making the presence of the system invisible to the user. Pervasive computing envisioned by Mark Weiser emerged at the conjunction of research and development in a number of areas which include embedded and devices and systems, wireless communications, and distributed, mobile and context-aware computing. This paper provides an overview of constituent components of pervasive computing and outlines the current progress made as a result of convergence of these areas of research.

Index Terms—Pervasive computing, embedded and mobile devices, context awareness, mobile computing

I. INTRODUCTION

THE concept of pervasive computing is based on a simple idea that with advances in technology, computing equipment will grow smaller and gain more power; this would allow small devices to be ubiquitously and invisibly embedded in the everyday human surroundings and therefore provide an easy and omnipresent access to a computing environment. In his seminal paper describing early ideas of developing such a pervasive environment [32], Mark Weiser presented a system that included three classes of computing devices: tabs, pads and boards. The design of each of these devices was suggested by the functionality of the similar office instruments [31]. Like Post-It notes, tabs were small devices designed for writing small notes; they were location-aware and had a pressure sensitive screen. Larger than tabs, pads were wireless pen-based notebooks, similar to writing pads. Boards were significantly larger, wall-sized interactive surfaces, similar to office whiteboards. In spite of the fact that the development of these devices did not go beyond early research phases at the Xerox PARC labs, they sparked a significant interest in the research and industrial community due to their potentially significant impact on the way how people interact with computing technology.

The fundamental properties of a system comprised of tabs, pads and boards described by Weiser include wireless communications, embedded and mobile devices, distributed computing, and context awareness. Although none of these concepts are new, each of them has experienced a dramatic

growth in recent decades reaching out into practical domains which, until recently, would not seem very applicable. For example, wireless communication was pioneered at the end of the XIX century, yet recent advances in development of mobile devices and efficient telecommunications technologies have led to an unprecedented growth in use of mobile telephones and a widespread popularity of rich media available to their users. Global connectivity provided by the Internet and cheap bandwidth took the concept of distributed computations pioneered in the early 1970's into the era of grid and utility computing. The fundamental principles of pervasive computing systems available anytime and anywhere evolved from the convergence of the same diverse technologies and concepts comprising the system envisioned by Weiser.

Pervasive computing is one of the many areas of computer science where academic research (e.g. context awareness and efficient telecommunications protocols) seamlessly integrate with advances in the industry (e.g. hardware and software for mobile devices and embedded systems), which results not only in wide availability of hardware platforms for research, but also in the rapid adoption of academic research outcomes by the industry [2,4,13]. As in any emerging research area, there are many challenging problems in pervasive computing. One of the most important and open questions is how to ensure that a computing system is seamlessly and invisibly embedded in the environment and how to minimize the possible impact of its intrusiveness on a user's perception. Generally, there are two mutually complementing approaches to solving the problem of unobtrusiveness of a pervasive system: by miniaturization of devices and embedding of the system's logic into wearable, handheld, and mobile devices, as well as into the environment, and by achieving a level of intelligence of the system that will be able to anticipate the actions of the user in the context of the factors in the environment. As a result, such a pervasive system will "fade into the background" and the users will only need to interact with such a system at their leisure without giving it much thought [14,23,28,30,32]. Research and development in pervasive computing systems has come a long way from tabs, pads and boards; however the underlying theoretical and technological concepts still remain the same. This paper examines the modern conceptual framework of pervasive computing systems and presents an overview of its constituent areas. The paper also outlines the current state of the art in using mobile and smart phones as devices that enable pervasive computing environments.

II. COMPONENTS OF PERVASIVE COMPUTING SYSTEMS

According to Weiser [32], pervasive computing systems create or are a part of an immersive, completely connected environment which becomes completely integrated with normal surroundings and become indistinguishable from them. To a large extent, technological solutions comprising the fundamentals of a pervasive computing system are already in place; it is just a matter of finding better and more efficient ways of their integration [10,25,28]. Thus, pervasive computing emerged at the conjunction of the following areas: embedded and mobile devices and systems, wireless communications, and distributed, mobile and context-aware computing.

Continuous progress in integrated circuit and processor design engendered a proliferation of ever more powerful and smaller computing devices. Processor power of today's smart phones may approach that of some desktops a decade ago [27]. Miniaturization and complex circuit design provides the capability to embed computational logic into a variety of devices, ranging from toasters, shavers and picture frames to automobiles capable of parking themselves or adjusting to the road and traffic conditions to home appliances that can communicate with each other [11,22]. Such a convergence of computational ubiquity and device embedding provides a mechanism for adjusting the users' perception and making these systems more physically invisible. Devices embedded into the environment require wireless communication capabilities in order to ensure the system's invisibility and to enable communication across multiple devices or components of a pervasive computing system. Pervasive systems typically use commonly available wireless communication technologies, such as Wi-Fi, Bluetooth and RFID sensor technology [8,29]; existing communication protocols are used alongside with those designed specifically for pervasive systems [18]. Pervasive computing systems also benefit from the decades of research in distributed computing, taking advantage of concepts and algorithms designed for remote access, high availability and fault tolerance [10]. The convergence of these existing and well-established fields is essential, but insufficient for further successful development of pervasive computing systems.

In addition to making the system physically invisible, the concept of pervasive computing provides for making systems logically invisible. Such a logical invisibility can be achieved if the system can adjust itself to the behavioral patterns exhibited by its user and to the factors of the surrounding environment, which include time, location, other users, objects and systems. Such capabilities can be achieved through context-awareness, which is a necessary component in providing the system's logical invisibility to complement its physical invisibility ensured by device embedding [28].

The remainder of this section examines the evolution of constituent components converging to implement the vision of pervasive computing.

A. Embedded and Mobile Devices

As predicted by Moore's Law, over several decades, processing capacity had doubled approximately every two years; it is now possible and commercially feasible to integrate computational logic into a wide variety of products, ranging from home appliances to automobiles [23]. As recently as a decade ago, it was impossible to imagine a networked computing environment comprised of anything smaller than laptops or desktop computers. Advances in the integrated circuits design technology made it possible to move some or all computational logic away from traditional components into the devices and parts of the everyday environment. With such a distribution and diffusion of computational resources into the general environment, it is increasingly important to address the problems of mobility in networks of heterogeneous portable devices. While traditional infrastructure-based communication systems typically provide networking services in static areas, pervasive computing systems face a range of unique issues caused by their ad-hoc and dynamic topologies; these issues include power management, location awareness and fault tolerance, which are discussed below [30].

Migration of computational power away from the desktop and into the general environment introduces new issues in human-computer interaction. Traditional input devices, such as keyboards and mice may no longer serve the sole tools of achieving system interactivity. The evolving concept of networked and cooperating devices transforms to embrace a diverse range of objects including car navigation systems and the elements of smart home environments; such a transformation will necessitate a departure from using many commonly accepted elements of the system input and output as traditional keyboards or mice – for a system blending into the surrounding environments, they will be to artificial. Today we witness an emerging trend to develop new methods of interaction that are more natural to humans, such as integrated touch screens [19], tabletop computing [21], or voice and gesture recognition systems [30]. Multimodality will play an increased role in providing more generic interfaces that make a provision for the limited availability of input and output devices [14].

Miniaturization of devices introduces a range of important problems concerning the aspects of human-computer interaction [11]. Existing mobile devices often have screens that are sometimes too small to display rich media content that can be found on the web [36]; keyboards are often too small or do not have enough keys to comfortably type long messages; batteries may not have enough capacity to support a prolonged use of the devices for power-consuming applications.

B. Wireless Communications

Wireless communication technology is an important component contributing to invisibility of pervasive computing systems [30,32]. Despite significant recent advances and unprecedented commercial success of mobile devices, wireless communications technology still remains a relatively young and rapidly growing field with very active research in many

critical areas such as, including signal interference, quality of service, privacy and security. Three categories of wireless communication standards dominate the field: protocols for personal area networks, local area networks standards (IEEE 802.11), and wide area networks (IEEE 802.16).

Personal area networks can be implemented using a number of technologies which include IrDA and Bluetooth. Infrared Data Association (IrDA) interface was one of the earliest commercial implementations; it is an infrared-based, short-range wireless communications protocol that supports a transmission rate of 115 Kbit/s. The most significant drawbacks of the IrDA technology included its dependency on having a direct line-of-sight, short range (under 1 m) and a relatively low transmission rate. Although IrDA enjoyed a brief period of popularity in late 90's and early 2000's among the developers of PDA's and laptops, it was replaced by more robust radio-based technologies that do not require a direct line-of-sight, have higher bandwidth and longer range. IEEE 802.15.1 standard commonly known as Bluetooth is a result of a working group established to develop a radio-frequency wireless standard that effectively replaces IrDA. Bluetooth provides transmission rates of up to 2.1 Mbps and does not require a direct line-of-sight for communication. Bluetooth has been designed for devices with low power consumption; current specification of Bluetooth standard provides for three classes of devices. Depending on the class, Bluetooth-enabled devices emit weak signals from 1 to 100 mW that provide the range of transmission from up to 1 to 100 meters. The limited range of Class 3 Bluetooth devices (up to 1 m) has been designed to reduce interference and it is ideally suited for many devices and applications, including cordless headsets, digital cameras and computer peripherals, such as printers, keyboards and mice.

Wireless communication protocols for local area networks are described in the IEEE 802.11 family of standards; current protocols of this family provide data rates up to 248 Mbit/s with outdoor range of up to 250 m (802.11g). These communications standards use radio-based transmission, which results in a significant potential for interference due to a longer signal range, and due to absorption and scattering by obstacles. 802.11 protocols have been widely implemented in consumer networking devices, and deployed in many industrial settings. Most existing wireless "hotspots" are powered by 802.11b/g/n standards. These protocols have been used by a significant number of initiatives to cover wider areas (college campuses, urban neighborhoods, and entire cities) with wireless internet access. However, an alternative technology exists that may be a better fit for such applications. WiMAX, the Worldwide Interoperability for Microwave Access, is a telecommunications technology based on the IEEE 802.16 standard aimed at providing wireless network access over long distances. Current WiMAX specification indicates data rates of 70 Mbit/s, which are achievable over very short ranges; more practical data rates of about 10 Mbit/s can be sustainably achieved over longer ranges, up to 10 km. Due to its

bandwidth and range features, WiMAX is well-suited for providing alternatives to such last-mile broadband technologies as cable and DSL, and providing network access to nomadic applications and users. Although WiMAX so far has not enjoyed a wide acceptance on par with 802.11 protocols, it has a very strong promise and a number of major telecommunication companies (including Sprint Nextel) are making significant investments to deploy their next generation of services using WiMAX.

Many existing mobile devices implement one or more wireless communication protocol in addition to their native cellular protocols. Many of smart telephones, including iPhone, incorporate both Bluetooth and 802.11 protocols [2,4,27]. As a result of integrating wireless communication capabilities, mobile devices become feasible components that can be easily and seamlessly blended into a pervasive computing system [8].

C. Mobility

It is increasingly important to consider the influence of device mobility on device and software architecture, and network infrastructures. The evident trend in device miniaturization introduces performance constraints that impact not only the device architecture, but also the viability of the existing network architectures such as wired local area networks and the global Internet [10].

Battery power is one of the most significant performance constraints suffered by mobile devices due to their need for an independent energy source, which typically is not an issue in traditional wired computing systems. Every single operation performed by the mobile device, from computations to communications, consumes battery power. Power consumption of the network interface and power-efficiency of communications protocols is usually not a significant issue in wired computing systems; however, its importance is elevated in wireless mobile devices. To resolve this problem, many wireless communications protocols have special provisions to conserve power. For example, power management schemes in IEEE 802.11 protocols provide for "sleep" states when mobile devices may turn off their transceivers during prolonged periods with no communication. Another possible approach to limiting a device's power consumption is to introduce a scheme to reduce the amount of power-consuming operations a device must run in order to accomplish a particular task. This challenge could be solved by introducing multiple levels of operability for devices within a pervasive computing environment; in this approach, long-term data storage and processor-intensive tasks are off-loaded or delegated to more resource-rich parts of the system, which would allow mobile devices to focus on less power consuming or high-priority local tasks [10].

Device mobility has a significant impact on the architecture of networked systems [1]. For example, tracking of devices roaming between areas of different types of connectivity and handling intermittent connectivity poses a range of open research problems [10]. There are many approaches to solving

mobility issues, such as the capability of mobile IP to handle handover and routing of roaming devices [17,33], many practical problems need the specifics of the application-level semantics, such as handling of data replication during device disconnections.

Furthermore, mobility has a profound impact on the design of software architectures for mobile and pervasive computing systems. Computing systems employing both wireless networks and mobile devices may require novel approaches to the software development [28,30]. Traditional system architectures may not be well suited for engineering pervasive computing environments, in which users and devices move around, triggering and producing a dynamic range of events, roaming through changing sets of heterogeneous resources, such as operating environments and input/output modalities. Pervasive computing systems comprise of a large number of sensors, devices and mobile systems; Software architectures that may be better suited to such an environment requires that the application logic be decomposed into atomic functions, which are distributed across ubiquitous processing, storage and input/output resources and that it be capable of reassembling in varying combinations as may be needed by a particular task. Service-oriented architectures enabled by XML Web Services [16,30,35] provide applications with such a modularity that complements the modular and distributed nature of pervasive computing systems.

D. Distributed Computing

Distributed computing is the process of dividing a computational task into a number of smaller sub-tasks to be completed simultaneously across a number of processors or computers. A distributed computing system is comprised of two or more interconnected and autonomous computing devices providing the capability to share logical and physical resources [3]. In the early stages of development, distributed computing was motivated by scarcity of resources; distributed systems were developed to share storage or processing power in order to solve computational problems that would be impossible to tackle on a single computer. Modern distributed systems often provide cost-effective alternatives whose performance is comparable to supercomputers. For example, distributed computing applications provide scientists and engineers with the opportunity to run computationally expensive simulation experiments involving very large data sets, such as astrophysical simulation; climate and weather modeling; and design of synthetic materials [5,24].

Distributed systems generally include components playing one of three possible roles: resources, resource managers, and clients [3]. Clients are the human users or other systems who access the services of a particular distributed computing system. Resources are either physical devices or objects connected to the system, such as printers, or logical objects, such as data files or databases, residing inside or controlled by the distributed system and available to the clients. Resource managers are software entities that regulate policies and access to resources within the distributed system. Typical distributed systems are said to have access transparency when resources are accessed through abstract interfaces, provided by the resource manager. Every resource within the distributed system has a unique identity, independent of the resource location. A distributed system is said to provide transparency of migration if it supports mobility of its resources. It is easy to see a number of parallels between the general architectural approach in distributed systems and pervasive computing systems. Device mobility, one of the key features in a pervasive system is mirrored in the distributed system architecture, which provides access to shared resources that are embedded into the environment of the system.

Very significant research background of distributed computing provides a solid conceptual foundation for pervasive computing [28]. Advances in active research issues of distributed systems, such as mechanisms for remote information access, security and privacy, high availability and fault tolerance play an increasingly important role in the development of pervasive computing systems.

E. Context Awareness and Invisibility

Context-awareness is a vital factor enabling the invisibility of pervasive computing systems [3,10,28,31]. Context-aware systems can adjust their properties and behavior according to the information about the current state of the user, such as physiological state, behavioral patterns, orientation and position, geographical location, or properties of the surrounding environment, such as time of day, nearby users, objects and other systems [6,15,26,28]

As a result of developing better mechanisms for enabling context awareness, pervasive systems are able to extend their capabilities and the range of services based on a potentially limited number of locally available resources [9]. For example, based on locality and availability, a context-aware service with limited resources may be able to off-load processor intensive operations or storage onto other systems located nearby that have more substantial resources. Current pervasive systems are capable of integrating a number of sources of context information and adjust their behavior to possibly unexpected situations or opportunities [34]. A vehicle navigation system that is aware of the remaining level of gasoline in the tank and the brand and type of fuel preferred by the user, may alert the driver when he or she is within certain proximity of a gas station selling that type of fuel at an acceptable price.

Invisibility in a pervasive computing system depends on how successfully it implements a certain level of intelligence that would enable it to allow the user to focus on a particular task at hand rather on interacting with the system itself [12]. Context-aware systems utilizing this type of intelligence often calculate the intent of the user based on a number of contexts. As a result, context-awareness helps eliminate the bottleneck of the human attention by anticipating the user's reactions to relevant events [9].

Most research on calculating user intent has been dispersed throughout many topical areas. In mobile and ad hoc

networks, user migration is often predicted based on past roaming behavior and current position; this process is primarily location-oriented and is controlled by the network infrastructure [3,6]. Pervasive computing systems need to anticipate the actions of the user and adjust themselves while maintaining a careful a balance between their proactivity and invisibility of the system. Maintaining a degree of invisibility is an important requirement for a pervasive computing system; if an application predicts user intent incorrectly, ineffectively or awkwardly, the presence of the system may be revealed. To make matters worse, adjusting incorrect behavior of the system would distract the user and require adjusting the system instead of focusing on the task at hand. However, if the system is too timid in predicting the user's intent, the system may compromise the concept of context-awareness because its behavior will not be noticed by the user. For example, suppose a user is viewing a video stream on a mobile wireless device [20]. As the user moves around, if the bandwidth becomes limited or the signal is affected adversely, a pervasive system should have the capability to dynamically adapt itself in response these factors without significantly altering the user's experience. What should be the appropriate reaction of the system in such a situation? If the network bandwidth becomes limited, the system may respond by switching to a connection with a higher bandwidth or provide the user with a lower fidelity video stream. Both of these outcomes are equally appropriate, but one of them may be more preferable based on user intent.

The ability of the system to adapt to changing factors in its environment is another important consideration of preserving the system's invisibility. Typically, pervasive systems need to adapt to the changes in availability of resources without revealing the inconsistencies in the supply of such resources as network bandwidth, available memory or processing cycles. Because of the nature of wireless communications (interference and delay due to atmospheric conditions or physical obstructions), it is difficult to provide connectivity guarantees in pervasive computing environments [3]; therefore provisions need to be made to ensure efficient and accurate data transmission. A number of strategies have been proposed to address this issue [28]. The system infrastructure could dynamically adjust the transmission fidelity based available resources. A pervasive system detecting that fewer resources are available to a device may choose to reduce the transmission fidelity, e.g. adjust the quality of a video streamed to a device from broadband to lower quality or, if necessary, to an audio-only stream in response to very low bandwidth availability; or to reduce the processing load on a device that is with a low power supply.

Alternatively, a reservation-based QoS scheme could be implemented where a user would request a specified level of service prior to participation. The network infrastructure of a pervasive system will be able to determine if there are sufficient resources to satisfy the user's requirements and to allocate these resources accordingly [7].

Finally, pervasive computing infrastructure could dynamically notify the user about the changes in resource availability and offer a choice of corrective actions. For example, when a bandwidth-constrained device is informed by the pervasive environment about alternative nearby locations with fewer users consuming the bandwidth, the use may receive a suggestion to move to that location in order to improve the transmission quality [9].

Despite the fact that some of these scenarios remain more conceptual than practical solutions, many of them are being pioneered in actual devices and systems both in research labs and in the consumer market.

III. MOBILE PHONES AND PERVASIVE COMPUTING

Integration of multiple functionalities into a single mobile device is a common trend in today's consumer electronics. Many mobile phones have photo/video cameras, GPS navigation systems, full keyboards, support multiple wireless communications technologies, and can run many applications supported by their operating system. A fundamental property of a pervasive system is to integrate into the environment and surround the users with its ubiquitous presence; smart phones can be the key interface device that connects the user to the pervasive computing environment. Anytime anywhere availability of pervasive services can be supported by the very nature of mobile phones that provide network access whenever needed and from any location. Today, mobile phones act as personalized end points for many information services. A number of academic and commercial projects offer such services as personalized shopping list management, mapping and navigation applications, and media streaming. Personalization is typically achieved by implementing different levels of context-awareness, which vary from rudimentary setting of user preferences [27] to intelligent profile matching [34]. Each mobile phone can be associated with a single individual and therefore used as a personal identification token. This feature is used primarily in mobile commerce: mobile phones can store personal information associated with a specific service (such as payment information and account login) which is used for authentication with these services either over a cellular network or directly with a payment facility using RFID or Bluetooth. For example, NTT DoCoMo introduced its RFID-based FeliCa service embedded in mobile phones that allows using it for mobile payments in many types of businesses, including mass transit systems.

In addition to enabling a broad range of specialized technical services, mobile and smart phones are a communication tool, which remains their primary functional feature. Today, mobile communication includes much more than interpersonal interaction, but also connectivity, content consumption and creation [4]. Smart phones are not only convenient and highly accessible devices, they are also capable of consuming and producing content, such as audio, images, video, and text. Originally designed as a communication

device, mobile and smart phones have become a tool supporting a broad range of rich social interaction providing their users with access to pervasive information services available anytime and anywhere [1].

Today's smart phones emerged from the convergence of mobile phones and PDAs inheriting the best features of both. However, mobile phones played a dominant role since smart phones remain predominantly communication devices with additional computational functionalities, which is clearly reflected in the design of smart phones. One can observe a certain analogy between the evolution of smart phones and personal computers [4]. Originally, PCs were designed to be mere desktop calculating machines modeled after minicomputers. With the emergence of the Internet, PCs evolved from being a tool for creation of content and data storage to a fully-fledged communication device offering a wide range of services, such as email, instant messaging, voice over IP, web browsing and publishing, access to streaming media, and many others. Rich communication capabilities of PCs allowed researches envision the paradigm of pervasive computing, which is grounded in seamless interaction among diverse devices unobtrusively embedded in the environment. However, it is the advent of smart phones that enabled us to approach the implementation of pervasive technologies.

IV. SUMMARY

Pervasive computing has emerged as multi-disciplinary area of research and development. Constituent disciplines and technologies bring years or decades of established results to the area of pervasive computing. However, it is in the convergence of these diverse areas, that brand new issues have emerged and provided the research and development community with a new frontier. From the original ideas of intelligent computing systems available anytime and anywhere developed by Mark Weiser over 25 years ago, pervasive computing has evolved into a prolific discipline where research goes hand in hand with practical developments that are brought to the forefront of consumer market. Many technological advances made by the academia and the industry led to a plethora of systems and devices with a wide range of capabilities, many of which have been enthusiastically embraced by the consumer. As Weiser wrote [32], "tabs, pads, and boards are just the beginning [of pervasive computing systems]. The real power of the concept comes not from any one of these devices; it emerges from the interaction of all of them." Today, mobile and smart phones have established themselves as a ubiquitous device that offers a variety of functions in addition to anytime anywhere connectivity, which remains to be the main attraction to mobile users. It is the human nature to strive for connection with other individuals, groups and activities, which can be fulfilled by pervasive environments providing access to ubiquitous information services. Mobile and smart phones are currently positioned as the best tool to access such services until there are more natural and practical interfaces providing for a better interaction with pervasive environments.

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Stan Kurkovsky is an associate professor at the Department of Computer Science at Connecticut State University. Stan earned his PhD from the Center for Advanced Computer Studies of the University of Louisiana in 1999. Results of his doctoral research have been applied to network planning and industrial simulation. Stan's research interests are in mobile commerce and pervasive computing, distributed systems and software engineering. His current research is focused on intelligent mobile systems, which include context-aware m-commerce and recommender applications. He published over 40 papers in refereed proceedings of national and international conferences, scientific journals and books. Stan serves as a reviewer and a member of program committees on a number of national and international conferences. During his academic career, Stan received over a million dollars in funding from private and federal sources.