Pers Ubiquit Comput (2004) 8: 31–41
DOI 10.1007/s00779-003-0254-7

ORIGINAL ARTICLE

Puneet Gupta · Deependra Moitra

Evolving a pervasive IT infrastructure: a technology integration approach

Received: 10 April 2003 / Accepted: 10 September 2003 / Published online: 20 December 2003

Abstract Over the past five years or so, pervasive computing has emerged as a new computing paradigm with a great deal of appeal. Enterprises are increasingly showing interest in deploying pervasive information technology (IT) infrastructures to realise the perceived benefits offered by this new computing paradigm. However, a return on the investment and considerations of the currently deployed infrastructure is a constraint for businesses to invest in a pervasive IT infrastructure. Realising that the economics of an investment in a new infrastructure can affect the embracing of pervasive IT, we suggest an approach that shows how the existing technology solutions available in the market and deployed in an enterprise can be used to develop a pervasive IT infrastructure, thereby protecting investments and maximising returns. We present an evolution model to systematically and incrementally achieve a pervasive IT environment, and present guidelines for evaluating which services to develop first based on "evolving the existing infrastructure point of view." This work provides practical implications for enterprises as well as pointers for research.

Keywords Information technology (IT) · Pervasive computing · Pervasiveness quotient (PQ) · Technology integration · Ubiquitous computing

1 Introduction

The vision of ubiquitous computing Mark Weiser painted several years ago is gradually turning into reality [1]. Over the last five years or so, interest in and research on pervasive computing has gained significant momentum. As an emerging computing paradigm, pervasive computing is generating much appeal both within academia and industry. Various definitions of and approaches to pervasive computing have evolved. For our discussions, however, we consider the following definition (found on the Internet without reference to any name) to be more appropriate and aligned to our view on pervasive computing:

Saturating an environment with computing and communication capability, yet having those devices integrated into the environment such that they "disappear".

The keywords in the above popular definition of pervasive computing are *saturating* (saturating an environment full of computation and sensory devices), *computing* (it's all about computing, isn't it?), *communication* (wireless connectivity), *integrated* (the integration of all technology components to provide user services), *environment* (smart spaces) and *disappear* (invisibility, minimal user involvement). These essentially constitute the basic characteristics of a pervasive computing environment.

While a lot of work has happened and continues to happen on developing pervasive computing environments [2, 3], we believe that the availability of a robust pervasive computing platform or environment will still not lead to its easy adoption in commercial settings. This is because most of the organisations have already spent quite a lot of money on installing their current information technology (IT) infrastructure, and while they find the promise of pervasive IT attractive, we envisage that new investments will pose considerable constraints in deciding in favour of a full-fledged pervasive IT environment. We believe that many of the elements that constitute a pervasive computing environment are already available in the market and deployed in organisations. Therefore, by integrating already deployed technology elements, a certain degree of pervasiveness can be achieved. The degree of pervasiveness can be enhanced by integrating more technology

P. Gupta (✉) · D. Moitra (✉)
Infosys Technologies Limited,
Hosur Road, Bangalore 560 100, India
E-mails: puneet_gupta@infosys.com; deependra_moitra@infosys.com
Tel.: +91-80-8520261
Fax: +91-80-8520740

elements into the environment, implying incremental costs and increasing the benefits of a pervasive IT environment.

In this paper, we look at pervasive computing from an enterprise IT infrastructure point of view. Whereas we believe that the implementation of truly pervasive IT systems is still many years away, building pervasive characteristics through technology integration in enterprise IT infrastructure can add a lot of value to enterprises even today. In our opinion, pervasive computing in an enterprise context is about the incremental integration of individual characteristics of a pervasive environment into the enterprise IT infrastructure, and slowly evolving towards a higher degree of pervasiveness by integrating additional capabilities offered by relevant technology elements.

In the enterprise context, we define pervasive IT as "an umbrella of IT capabilities working together to provide services to end users characterised by mobility, wireless connectivity, context awareness, implicit inputs (including user intent), proactiveness, smart spaces (an environment that can interact with users and devices), and the use of natural interfaces for human-device interaction." The ultimate objective of a pervasive IT infrastructure is to provide as much distraction-free (invisibility) interaction as possible between the user and the IT infrastructure, and to have the environment collaborate with the user in performing the tasks at hand more effectively.

As mentioned above, many of the hardware and technologies needed to realise an enterprise pervasive IT infrastructure are commercially available today. Therefore, enterprise pervasive IT in our opinion is primarily an integration and software challenge. We further make a distinction between pervasive IT from an infrastructure point of view and from the user perception point of view. A pervasive IT infrastructure may possess or exhibit the basic pervasive computing characteristics, but for the user to perceive a pervasive computing environment, the pervasive characteristics need to be bundled together in the form of services, which the user can take advantage of. The enterprise pervasive IT evolution roadmap we present in this paper reflects this, where we show a pervasive "services" infrastructure—a software skin over the pervasive IT infrastructure—as a distinct and evolutionary stage from the pervasive IT infrastructure, which is primarily an infrastructure enriched with pervasive computing characteristics.

In the next section of the paper, we provide an overview of the current scene in pervasive computing. The rest of the paper is organised as follows: In Sect. 3, we present a model for the evolution of a pervasive IT infrastructure. Guidelines for evolving a pervasive IT infrastructure are presented in Sect. 4, and Sect. 5 presents a generic architecture for enterprise pervasive IT infrastructure. Sect. 6 captures the benefits the suggested approach provides, and Sect. 7 provides a summary of our contributions and outlines future directions for further work.

2 The current scene

Pervasive computing has witnessed significant research activity in the last few years both in academia as well as industry. Most of the research initiatives are either focused on specific aspects of pervasive computing or are umbrella projects with several aspects being investigated. Some of the better-known initiatives in academia include project Oxygen at MIT [4], project Aura at Carnegie Mellon University [5], the Portolano project at the University of Washington [6] and project Endeavour at UC Berkeley [7]. Notable research initiatives within the industry include EasyLiving (Microsoft) [8], Cooltown (Hewlett-Packard) [9], and IBM (an extension of the WebSphere middleware platform) [10]. Some of these R&D initiatives are aimed at demonstrating a complete pervasive computing environment, while others focus on specific aspects such as the middleware, the user interface, etc.

While all these research initiatives are important for a full-scale realisation of pervasive computing, what seems to be missing in our opinion is concrete work on deploying pervasive services in enterprise today. We believe that an appropriate and cost-effective way forward is to integrate already available technologies in order to achieve limited pervasiveness in the IT infrastructure and in order to derive some immediate business benefits. This will provide the enterprise an opportunity to assess the extent of benefits from a pervasive IT set-up, and the incremental results, in turn, will both spark more interest and investments in pervasive IT.

The mobile IT infrastructure has already attained a fair level of maturity, and increasingly wireless capabilities are being incorporated into enterprise IT infrastructures. These capabilities, viz., mobility and communication, are a fundamental part of pervasive computing. Therefore, it is imperative that more and more pervasive computing capabilities be added to the existing infrastructure capabilities, and applications developed that demonstrate the benefits of the pervasive computing paradigm while allowing for gradual, structured investments. This paper is aimed at sparking interest in this aspect of research in pervasive computing, and the model we present provides for a structured roadmap for evolving a pervasive IT infrastructure through the process of technology integration.

3 A model for the evolution of a pervasive IT environment

The concept of pervasive computing is a paradigm shift from a traditional IT point of view, including to a large extent mobile IT. However, from an enterprise point of view, treating pervasive IT as a radical departure from the traditional IT presents a dilemma. While on the one hand, there is an opportunity to derive productivity and business benefits from an intelligent IT infrastructure

built on the pervasive computing paradigm, on the other hand, there is a need to protect investments already made in the existing IT infrastructure, including mobile IT. We therefore suggest that the enterprise pervasive IT be modelled as a gradual evolution from an existing IT infrastructure point of view. In the enterprise pervasive IT model (EPIM) we propose in this paper, we provide a roadmap for evolving today's IT infrastructure into a pervasive IT infrastructure.

Note that the entire approach essentially consists of two parts. Part one (Table 1, Fig. 1, Fig. 2, Table 2, and Table 3) is the evolution roadmap, which provides a structured approach for the evolution of the overall enterprise IT infrastructure towards achieving the goal of a completely pervasive IT. Part two (Fig. 3), is the enterprise pervasive IT model, which models the pervasiveness of an IT infrastructure in terms of the pervasiveness quotient (PQ).

Table 1 What constitutes pervasiveness in an enterprise pervasive infrastructure?

Attributes	Comments
Mobility	Of users and services
Invisibility	Minimal user distraction
Wireless communication	Indoor and outdoor
Smart spaces	Intelligent surrounding with sensing, computation and communication capabilities
Localized scalability	Scaling the interaction between the users and surrounding according to relevance. More interaction with nearby objects and less communication with objects far away
Context awareness	User contexts, time contexts, network contexts, nearby object and users' contexts, lower level and higher level contexts
Uneven conditioning	Masking uneven penetration of pervasive capabilities in the infrastructure
Personalisation	Based on context, transcoding, etc.
Security	User level, service level, context level, location-based, etc.
Privacy and trust	Maintaining privacy across different access channels
Proactivity	Based on smart spaces, device-device communication and context awareness
Capturing user intent	Based on context, history, intelligence
Natural/alternate interfaces	Biometrics, voice IO, video, pointing, gestures, etc.
Ad hoc networking	
Cyber foraging	Computation capabilities in the environment which can be leased out to devices requiring more computation capability than they have for a particular task
Adaptation and QOS	Network and application character
Capture and access to live experiences	
Interruption free infrastructure	Fault tolerance

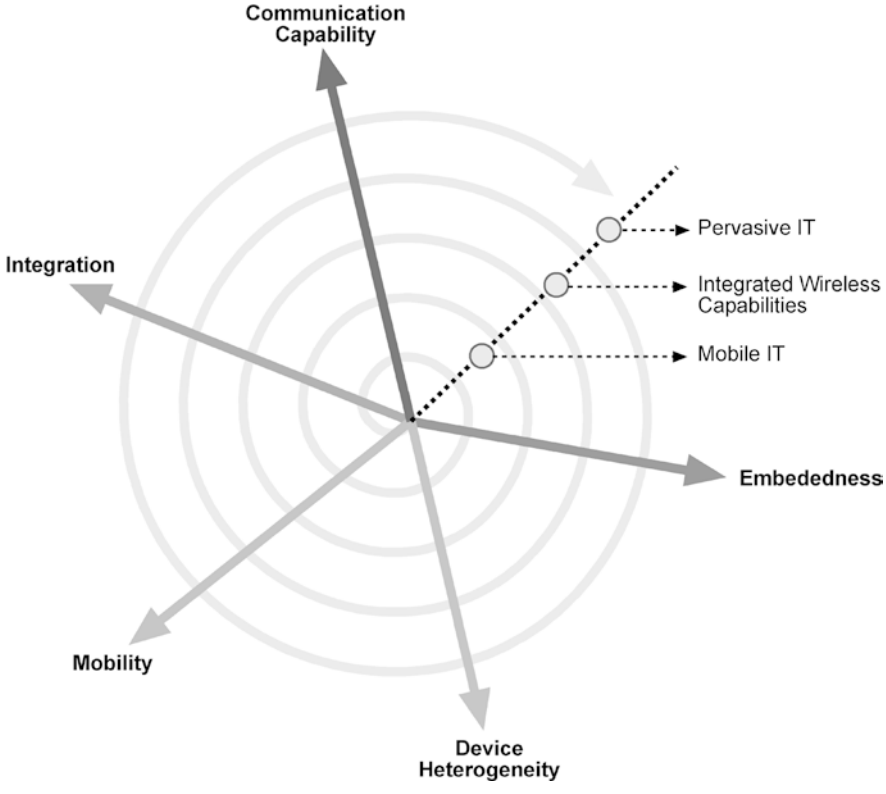

Fig. 1 An evolution towards a pervasive IT infrastructure

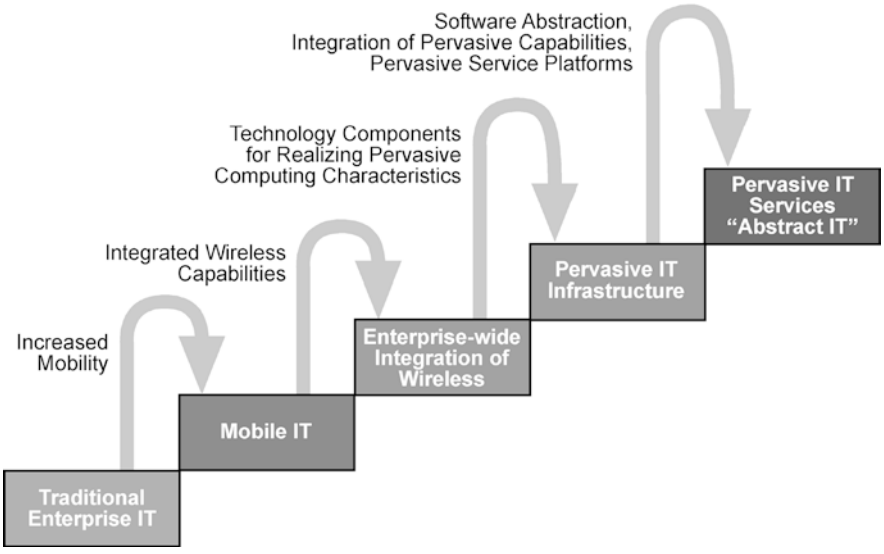

Fig. 2 An enterprise IT evolution roadmap

In our opinion, the evolution to pervasive IT is characterised by a marked increase in mobility, embeddedness, IT integration, device heterogeneity and the communication capability from an infrastructure point of view, as depicted in Fig. 1. These basic characteristics and other attributes—primarily derivatives in nature—such as adaptivity, smartness (intelligent infrastructure), localised scalability, uneven conditioning and context sensitivity are the basis for the EPIM.

In the enterprise pervasive IT evolution roadmap, the enterprise IT evolution is seen as a five-stage process, as shown in Fig. 2 and detailed in Table 2. When viewed in conjunction with Fig. 1, the individual stages in the roadmap can be seen as achieving an increase along the five basic attributes as the progression to higher stage is realised. The extent of the increase in each of the five attributes depends on certain key aspects that characterise each stage, which in turn are dependent on the enterprise business ecosystem. It may be emphasised that we have considered wireless adoption as a stage distinct from mobile IT, as this helps in clearly identifying the nature of evolutionary changes and their benefits towards acquiring real-time capabilities. This is also supported by actual adoption trends of mobility and wireless capabilities by enterprises around the world. Also, we position pervasive IT services as distinct from the pervasive IT infrastructure, and hence have shown this as a separate stage in the model. In the ''pervasive IT infrastructure'' stage, the focus is on infrastructure capabilities that are required to realise pervasive services. In this stage, selective pervasive IT services will exist, though disjointed from non-pervasive services. It is only in the ''pervasive IT services'' stage that the pervasive IT infrastructure, augmented with service platforms, is expected to attain adequate maturity, resulting in pervasiveness becoming a common character of all IT services. In this stage, where service platforms (middleware) will allow for the rapid deployment of new pervasive services, the difference between the pervasive and non-pervasive applications is expected to disappear.

In Table 2, we define each of the five stages of the enterprise pervasive IT evolution roadmap in terms of IT infrastructure characteristics, an enterprise ecosystem and key business benefits. In Table 3, we provide a roadmap for a transition (evolution) between the stages in terms of the incremental business benefits, new technology adoption, integration efforts and operating costs, etc. The specific IT characteristics and transition characteristics are bound to differ from one industry segment to another. One of the goals in our attempt to develop the EPIM has been to ensure that the model is general enough so that it can be applied across verticals. A discussion on the customisation of the model to suit a particular industry segment is beyond the scope of this paper, and is an area for further work. As a pointer, at a first level, customisation would require a detailed characterisation of the enterprise and its business focus, its business priorities and the typical application areas at each level of the EPIM depending on the nature of the industry vertical.

The detailed analysis of the individual stages in the enterprise IT evolution and their characteristics, as shown in Table 2, establishes that in the enterprise context, pervasive IT is not a completely distinct stage in IT evolution; rather, it is about gradual increase in the degree of pervasiveness in the IT environment, or the PQ. The PQ is a measure of the extent to which the IT infrastructure shows pervasive characteristics like smart spaces, context awareness, invisibility, user and service mobility, localised scalability, proactivity, interruption free interfaces, etc. The characteristics mentioned above are not exhaustive, but represent the key characteristics (see Table 1 for other pervasive characteristics). The essence of this reasoning is that in each stage of the IT evolution one can see an increase in the PQ, and in our view, the goal of the evolution of enterprise IT to enterprise ''pervasive'' IT is to gradually increase the PQ

Table 2 Enterprise pervasive IT evolution roadmap

Stage	IT Infrastructure characteristics	Enterprise characterisation	Key business applications
Stage 1	Computing PC centric	Communication across business functions, partners and other parties mainly via the Web	Web enabling processes and workflows
Traditional enterprise IT	No organised introduction of mobility in the IT infrastructure Low level of automation	Focus on enterprise wide integration of business systems and workflow automation	Use of IT for ERP, SCM, CRM and organisation value consolidation
Stage 2	Adoption of mobile technology. Mobile information access integrated into the enterprise IT system	Increased focus on mobilising the workforce	Mobile CRM (mCRM)
Mobile IT	Mobile applications primarily for field force professionals and basic PIM	Enterprise characterised by increasing mobile work force	Mobile SCM (mSCM)
	Wireless capability missing or limited to cellular access for field personals	Focus on Customer relationship management (CRM), supply chain management (SCM) optimisation	Increasing the efficiency of dispatch, inventory management, etc.
	Automation still low. Islands of automation exist		
Stage 3	Adoption of wireless technology (both cellular and WLANs)	Increased focus on enterprise-wide mobilisation of the workforce, on productivity enhancements as well as managing supply chains in real time	Real-time handling of CRM, SCM, inventory control and dispatch, etc.
Enterprise-wide integration of wireless	Widespread use of mobile devices across the organisation in new user segments like knowledge workers with wireless e-mail access	Collaborative work environment	
	Introduction of platforms for transaction management, device management, content transcoding and mobile security Support for ad hoc networking Automation widespread across the organisation	Emphasis on real-time management of the enterprise and its critical value chains	
Stage 4	Introduction of pervasive infrastructure capabilities like "context sensing", "smart spaces", efficient management systems for device heterogeneity, "location awareness" and software infrastructure for managing user contexts and their contextual relationships with other users and objects in the surroundings	Focus on collaboration, automation, real-time management, productivity enhancement and real-time networking with known and ad hoc partners	Automation and optimisation of supply chains and inventory management
Pervasive IT infrastructure	Introduction of new short range wireless technologies such as Bluetooth, infrared, etc. A strong communication infrastructure. Always-on connectivity		Achieving high levels of productivity in collaborative and ad hoc environments Applications for enhanced customer service experience using interactivity, context-sensitivity and proactiveness
	Introduction of content management and personalisation platforms, bandwidth management systems, voice platforms, etc. Substantial increase in the level of automation, particularly that related to physical infrastructure		
Stage 5	A software fabric encompassing the entire pervasive IT infrastructure providing infrastructure abstraction and providing all pervasive computing capabilities as services to other applications	Highly collaborative (within the enterprise and with other value chain members), operates in real-time, highly automated and with extremely mature and flexible business processes	Automation and optimisation of supply chains and inventory management
Pervasive IT services – "Abstract IT"	At this level, pervasive IT environment is very well integrated with the other enterprise IT systems		Automation of workflow across the enterprise and other value chains
	System operates in a very proactive manner and lots of transactions happen invisibly (without user intervention) based on user and environment contexts and implicit input sensing		Optimised enterprise resource planning and CRM
	New applications can be rolled out very fast without any concern about the underlying infrastructural details Increased automation of transactions and in business processes		Infrastructure support for real-time decision making

Table 3 Enterprise pervasive IT transition characteristics

Transition	Incremental business benefits	Transition characteristics (cost, new technology adoption, integration, etc.)
Stage 1 to 2	Increased efficiencies in supply chain, inventory control, dispatch and customer relationship functions	Transition typically characterised by new technology adoption (mobile devices, synchronisation systems) and a relatively low level of technology integration
	This transition typically triggers IT initiatives into mobile security and device management, which act as the basis of further mobilisation of enterprise in future.	Primary running costs are related to procuring and maintaining devices. Fixed infrastructure costs involve synchronisation software, device management software and security infrastructure
Stage 2 to 3	Adding real-time transactions to the previously synchronisation based mobile communication model	Transition typically characterised by new technology adoption (wireless LAN setup, wireless modems (WLAN, cellular) for mobile devices (laptops, PDAs)) and a medium level of technology integration. Platforms for transaction management, device management, content transcoding and mobile security, etc. need to be introduced
	Wireless access to e-mail and intranet access can lead to improved productivity	Primary running costs are related to procuring and maintaining devices and communication costs. Fixed infrastructure costs involve WLAN setup, device management software, security infrastructure and other middleware platforms
	Mobility across the enterprise can lead to more collaborative work environments. IT infrastructure more conducive towards handling ad hoc structures Wireless capability gained at this stage is a primary requirement in the next stages of the pervasive IT evolution	
Stage 3 to 4	This transition marks the addition of pervasive characteristics such as context-awareness, smart spaces and location-sensitivity. Key business benefits involve:	Transition typically characterised by new technology adoption (context sensing including location sensing, smart space infrastructure like displays, radio IDs (e.g., RFIDs) and radio devices such as those based on Bluetooth, infrared, etc.) and a high level of technology integration (software integration of different user and environmental contexts, integrating user and world model with other applications, integrating voice and other IO mechanisms)
	better collaborative setups	Primary running costs are related to maintaining smart spaces, context sensors, short-range radio communication infrastructure and communication costs. Fixed costs include middleware software, software development, setting up the sensor and radio infrastructure, security infrastructure, and privacy and trust mechanisms
	higher degree of automation Location and radio tagging capabilities can be used in asset location/tracking applications and inventory management, etc. Security can be enhanced by introducing location-based access control and smart labels	
Stage 4 to 5	This transition marks the migration from a pervasive IT infrastructure to a pervasive IT "services" infrastructure, where the pervasive IT infrastructure is optimised via a software abstraction towards quick and easy roll outs of new pervasive applications allowing the significant realisation of business advantages. A high level of integration means pervasive services are available to all enterprise applications that can make any use of them	Transition typically characterised by a relatively low level of new technology adoption but a very high level of technology integration. This transition is primarily software intensive and will involve intelligent software layering with a view to maximising the benefits offered by the underlying pervasive IT infrastructure. This transition will also see additional pervasive IT capabilities based on the experiences gained in the previous stage. High levels of enterprise application integration will be involved. The modification of existing application base to include pervasive characteristics may also be involved Primary running costs are related to maintaining and updating smart spaces, context sensors, short-range radio communication infrastructure and communication costs. Fixed costs include middleware software, software development

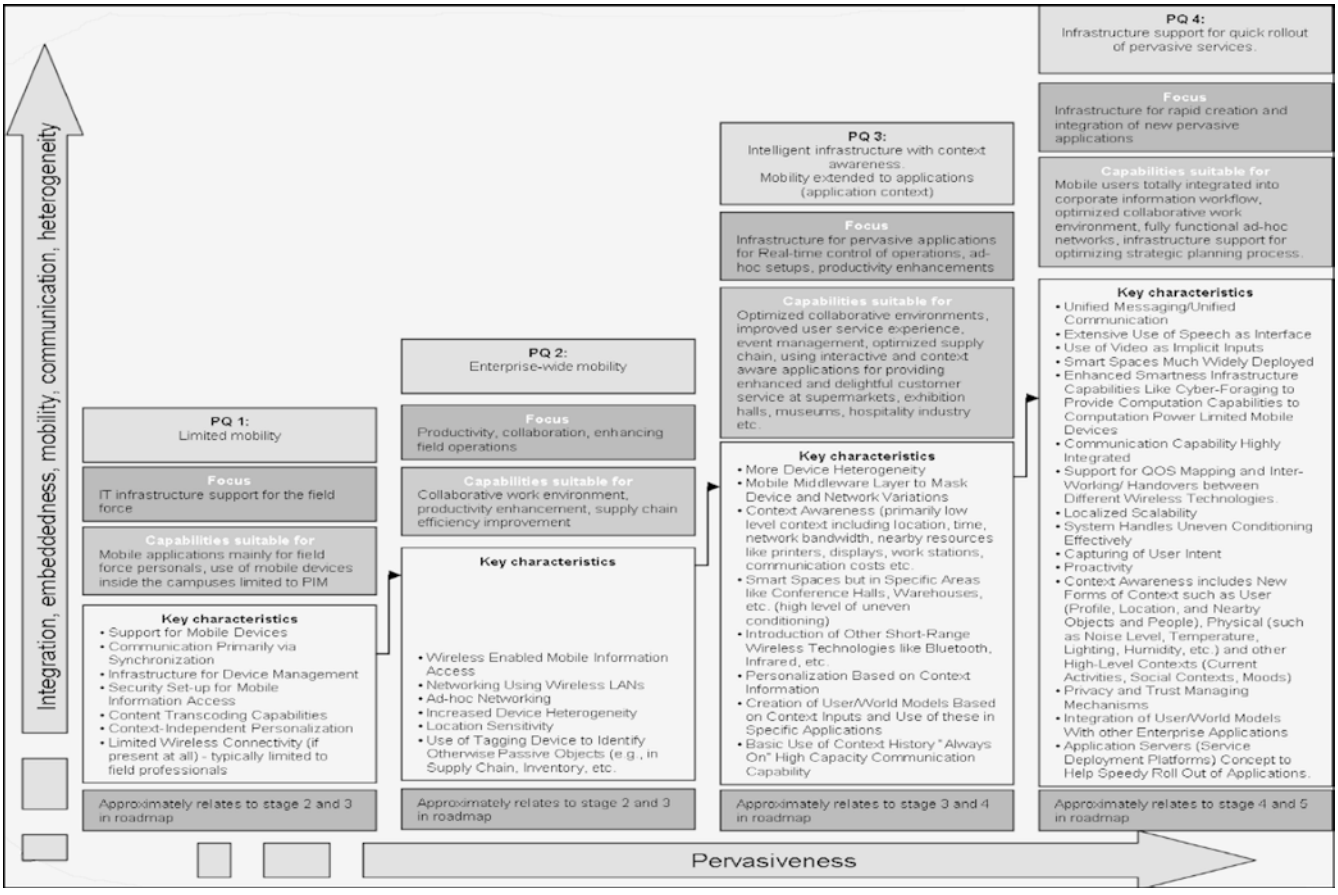

Fig. 3 An enterprise pervasive IT model

to a level which is optimal for a specific business in a given context. Also, the achievement of a higher PQ is to be harmonised with the objective of preserving the existing investment in IT systems.

Considerations such as those stated above have influenced the development of the EPIM we present in this paper (Fig. 3). The key inputs and considerations that have gone towards the development of the model are as follows:

- The evolution to a pervasive IT is about gradual increase in the PQ
- How does one arrive at the PQ of an enterprise IT system?
- What is the optimal PQ for a particular enterprise, given its business context?
- What basic pervasive characteristics are needed in a specific type of business ecosystem?
- For an enterprise evolving from a particular PQ to another, what are the key infrastructure areas to be focused on?

We have not attempted to quantify the pervasive quotient because we don't yet know of a unique way in which this can be done. Rather, we take a more generic approach based on the key pervasive characteristics that are relevant from an enterprise point of view. EPIM defines four levels in terms of PQ, where, for example, Level 1 means a PQ of 1 for the enterprise pervasive IT infrastructure, as shown in Fig. 3. A higher level shows a progressive increase in the PQ, compared to the previous level. Each level shows a typical set of pervasive IT capabilities that an IT infrastructure at that level should possess. Each level only lists the new pervasive capabilities and this means that an IT infrastructure with a PQ of 2 has these new capabilities along with the capabilities of an infrastructure with a PQ of 1. Also, note that only the pervasive computing characteristics have been captured in this table. There are other IT infrastructure components that may not be specific to a pervasive IT as such but are extremely important if a pervasiveness of IT infrastructure is to be taken advantage of. These include aspects like a supply chain management infrastructure, the extent of the automation of systems and processes using automation software, the integration of enterprise applications, content aggregation/management/personalisation platforms, portal platforms, transaction platforms (e.g., e-payments), storage platforms, business intelligence software, etc. Then there are aspects like bandwidth management, broadband strategy, wireless strategy, convergence strategy, exposure to Web services, etc. It is important that these figure in the overall enterprise IT infrastructure evolution plan.

4 Guidelines for the evolution of a pervasive IT environment

Figures 4 and 5 depicts the relationship between the EPIM (Fig. 3) and the enterprise pervasive IT evolution roadmap (Table 2). As shown in Fig. 4, pervasiveness is distributed across stages with each higher stage in the enterprise pervasive IT evolution characterised by a progressive increase in the PQ. Any given stage in evolutionary roadmap, even though related to a PQ, is not intended to have a strict mapping with it. PQ talks about maturity in terms of pervasiveness and not exactly in terms of general IT infrastructure maturity. Certainly, both have a relation but nothing that can be exactly specified. For example, Fig. 4 shows that an enterprise with a PQ of 2 can possess the characteristics of stage 2 (mobile IT) as well as stage 3 (enterprise-wide integration of wireless networks) in an enterprise pervasive IT evolution roadmap. While trying to chart out an evolution roadmap to attain certain pervasive characteristics, the approximate mapping of the PQ level to a particular enterprise's stage in the roadmap needs to be resolved. This can be done by referring to the infrastructure and enterprise characterisation in the evolution roadmap (Table 2).

The purpose behind the EPIM is to quantify the PQ into certain levels so as to provide a structured roadmap for the evolution of a pervasive IT ecosystem. We hope that the enterprises can use the model to figure out where they exist in terms of the PQ, and where they should be in order to meet their business needs. Once the target and current PQ levels have been identified, the model can be used to determine the key pervasive characteristics and the technology capabilities that need to be introduced to reach the target PQ. This is where the pervasive IT evolution roadmap comes into the picture, which provides enterprises with a structured evolutionary path and guides them to systematically introduce more pervasiveness in their IT infrastructure. One can argue that once the desired pervasive characteristics have been identified, these can be implemented to realise the desired pervasive services. The flaw in this argument is that this makes no sense both from an implementation perspective as well as from an economic point of view. For the realisation of any pervasive characteristic there may be many other derivative or related capabilities that need to be developed and, therefore, it is important that a systematic approach be taken to gradually introduce the necessary capabilities in the infrastructure to maximise the returns on investment in new technologies and systems. This is what the evolutionary roadmap accomplishes. For instance, an organisation at stage two cannot achieve a PQ of three or four without evolving its IT infrastructure through stages three and four.

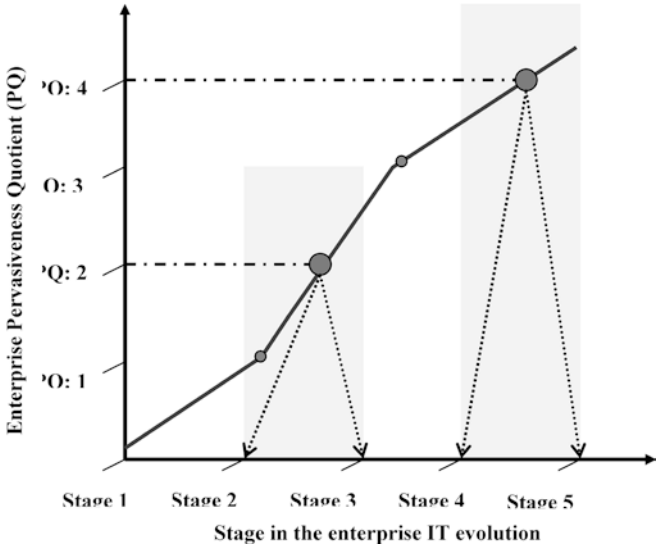

Fig. 4 A mapping of the Pervasiveness Quotient (PQ) to the stages in the enterprise evolution

Let us consider, for example, a knowledge-based enterprise[1] where the business restructuring has resulted in an environment that is characterised by temporary workgroups, ad-hoc set-ups and cross-functional teams. Clearly, the change in the enterprise structure requires that the IT infrastructure be modified/enhanced to cater to the new business setup. A pervasive IT infrastructure clearly has the characteristics that are suited for this kind of business structure. So, how does an enterprise go about adopting pervasive IT?

4.1 Step 1

A look at the EPIM (Fig. 3) will suggest that such kinds of applications and business environments would typically require a PQ of 3. The next task will be to determine the PQ of the existing IT infrastructure. Again, a reference to the same model (Fig. 3) would result in either a PQ of 1 or 2, based on the current business environment and IT applications. Let us assume that the enterprise is already mobile-enabled and has adopted wireless capabilities like wireless LANs. This would typically fit the enterprise in question in a PQ of 2. When the characteristics of infrastructures with PQs of 2 and 3 are compared, we would find some key pervasive characteristics that would need to be made part of the IT infrastructure. The comparison of typical characteristics for PQs of 2 and 3 will result in characteristics like low-level context sensing, smart spaces (in conference rooms,

[1]We define a knowledge-based enterprise as an enterprise that relies heavily on knowledge assets (the capture and transmission of knowledge artefacts), information exchange, employee-employee interaction and real-time decision making for successful functioning. Ideally, such an organisation needs an IT infrastructure that provides effective networking capabilities, the real-time flow of information and the ability to spontaneously scale and re-configure itself based on changing business requirements. In the context of this discussion, some examples could include a consulting and business analysis organisations, law firms, RD setups of organisations (pharma, IT, automobile, etc.).

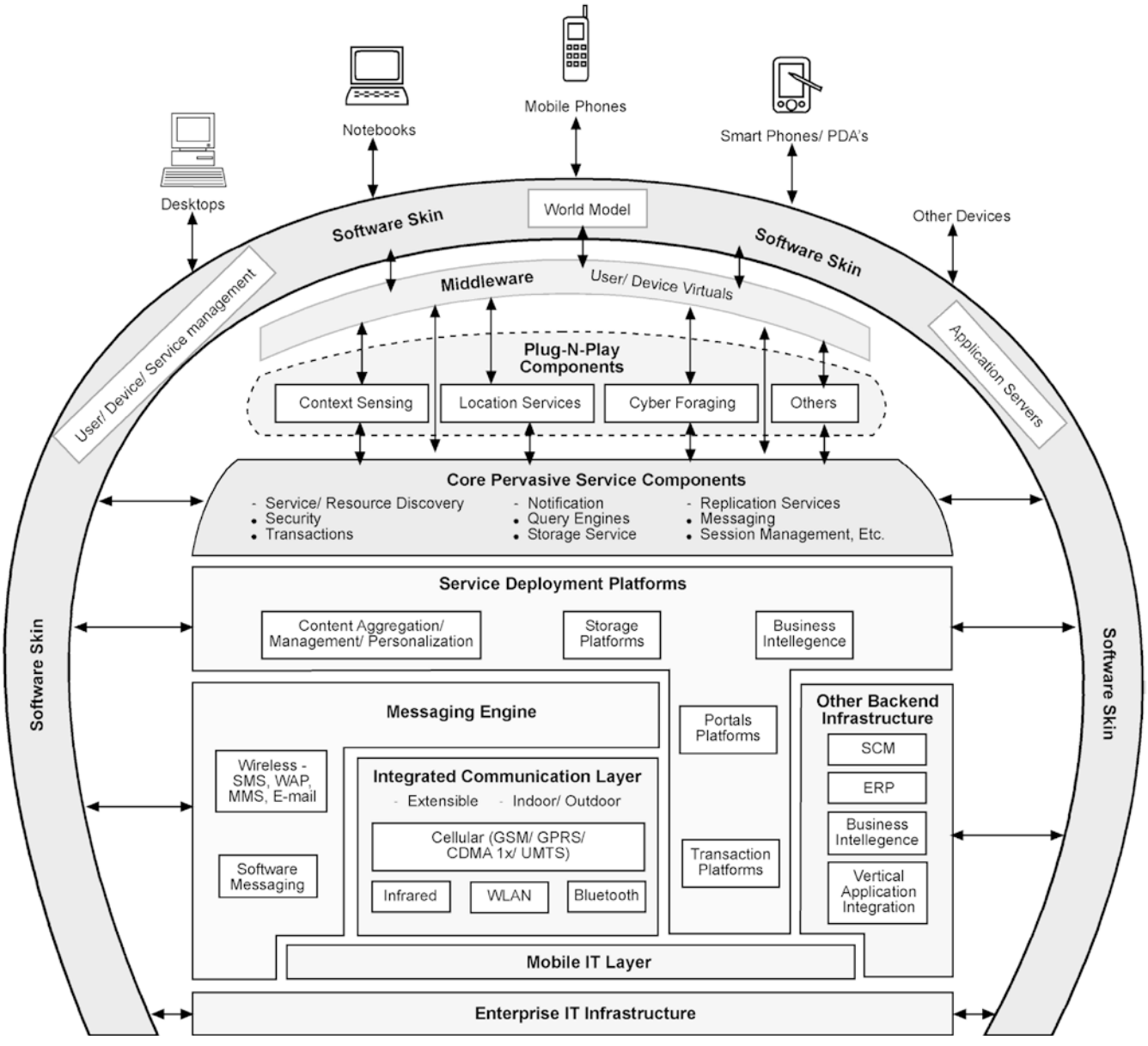

Fig. 5 A generic architecture of the enterprise pervasive IT system

etc.), short-range radio technologies like Bluetooth, infrared technology, etc.

4.2 Step 2

Next we need to refer to the evolutionary roadmap (Table 2) to chart out the right evolutionary path for the overall IT infrastructure to achieve the new pervasive characteristics identified in step 1. Referring to the "IT infrastructure characteristics" mentioned in the roadmap, the current stage in the evolution roadmap can be established. Let us assume that this results in the current state of that enterprise's IT infrastructure being at stage 3. Again, if you refer to the evolutionary roadmap (Table 2), stage 4 is the one with the new desired pervasive characteristics (context sensing, smart spaces, "always on" communication capabilities, etc.) we established in step 1. This means that the enterprise should plan a transition from stage 3 to stage 4.

4.3 Step 3

The last step in this exercise is charting out an evolutionary roadmap based on the inputs from the transition table (Table 3), which lists the transition characteristics (for stage 3 to 4) in terms of new technology adoption, integration, costs etc.

Note that such an exercise may typically result in a need to transition from stage 2 to stage 4. The model in this case would require two transitions from stage 2 to stage 3 and then from stage 3 to stage 4.

So, in general terms, the following process is recommended for planning the evolution of a pervasive enterprise IT infrastructure:

1. Using the EPIM, determine the kind of applications and IT support needed for your business competitiveness. Based on this, determine the target PQ.
2. Also, based on the EPIM itself, assess the PQ of your existing IT infrastructure.
3. Determine the gap between the target PQ and the current PQ, and using the EPIM, list the additional characteristics that need to be implemented in order to achieve the target PQ.
4. Determine what stage your current pervasive IT infrastructure on the EPIM roadmap is, and what stage will be appropriate for your business in order to operate at the target PQ.
5. Once the target stage and the current stage have been determined, using the EPIM Roadmap, plan the evolution into higher degree of pervasiveness.

It may be noted that for an enterprise pervasive IT environment to be at stage *n,* for example, it has to not only exhibit the pervasive characteristics of stage *n* but also that of all the preceding stages. It is possible and quite likely that one will find an enterprise partly fulfilling the characteristics of two adjoining stages (let's say, stage 2 and 3). In such cases, for a systematic evolution into a higher degree of pervasiveness, we suggest that evolution be planned with the lower stage as the baseline.

5 A generic Architecture for An enterprise pervasive IT infrastructure

We provide here a generic architecture based on the evolutionary view of pervasive IT infrastructure we have discussed so far.

Based on our EPIM, we suggest a plug-n-play architecture (Fig. 5) for an enterprise pervasive IT infrastructure whose PQ can be increased by adding new technology components and by means of integration. The overall architecture is based on an existing mobile IT infrastructure with a truly integrated communication layer. The communication layer consists of technologies like WLAN, Bluetooth, infrared and cellular technologies like GSM/GPRS/UMTS/CDMA1X and provides wireless connectivity as a service provided by the infrastructure. The communication layer should be extensible so as to allow both indoor and outdoor (cellular) wireless access depending on the context. A wireless capability is absolutely fundamental in the evolution from a mobile IT infrastructure to a pervasive IT infrastructure. The backend infrastructure for supply chain management, ERP, business intelligence, vertical applications integration, etc., remains as it exists in the mobile IT infrastructure context. As Fig. 5 depicts, on top of the basic mobile plus wireless platform, there exists some core pervasive IT components and some other components listed as plug-n-play.

The core components consist of services such as service/resource discovery, security, transactions, notification, query engines, storage services, replication services, messaging engine and session management, etc. The plug-n-play components concept is what allows for a gradual increase in the PQ of the infrastructure, allowing enterprises to gradually roll out pervasive services and then to evolve the infrastructure as the organisation gains experience and maturity with the new systems and user services. The plug-n-play components typically reside at the periphery of the pervasive IT infrastructure along with other components like mobile devices. As an example, plug-n-play infrastructure components could be those related to context sensing like location information (location sensors-transmitters, tags and other location sensing devices), infrared beaming, radio ID tags such as RFIDs, tracking capabilities and other sensors such as temperature, lighting, etc. As the PQ increases, it becomes critical that the software skin that encompasses the entire core and plug-n-play infrastructure doesn't need to be drastically modified every time new plug-n-play components are added. This is ensured by an additional middleware layer that represents all users and objects in the system by their "virtuals" thereby hiding the actual infrastructure details.

Whenever a new plug-n-play component gets added, say, indoor location sensing, only the corresponding virtuals of the concerned objects need to be updated with a new context definition. The system can now provide enhanced services by virtue of the fact that the smartness of the system (smartness is a fundamental characteristic of pervasiveness), and hence pervasiveness, has increased. The software skin that encompasses the entire pervasive IT infrastructure exposes the capabilities of the system in the form of application servers that allow new applications to be deployed and integrated with the rest of the IT infrastructure transparent to the underlying infrastructure. This concept not only allows for rapid service creation but also helps to evolve the pervasive IT infrastructure without impacting the applications that the user interacts with.

6 Benefits of the suggested approach

There are several characteristics of a pervasive IT environment that work together to realise a pervasive computing environment. Each of these characteristics is associated with several other derivative characteristics or technology capabilities that need to implemented. To an enterprise seeking to establish pervasiveness in its IT infrastructure, which characters, technologies and systems to deploy and in which order is a challenge. The model and the roadmap we have suggested aim to alleviate this problem by systemising the pervasive IT adoption process.

Some of the benefits of the EPIM and the associated roadmap are as follows:

- Providing a structured evolution roadmap to enterprises to systematically build a pervasive IT infrastructure while accounting for the existing investment in IT
- Helping enterprises evaluate their needs in terms of the pervasive IT capabilities (the PQ) they require in a given business context
- Helping to identify an enterprise's current IT infrastructure maturity in terms of its PQ, thereby allowing the enterprise to chart out an appropriate evolution strategy to achieve higher levels of pervasiveness.
- Helping map out the pervasive IT capabilities to the business ecosystem (enterprise characterisation).

7 Conclusions and future directions

The paper presents a model for a gradual evolution of an enterprise pervasive IT infrastructure. The model and the evolutionary roadmap can be used to make strategic decisions and plans concerning a pervasive IT infrastructure evolution. We believe the technology integration approach we have suggested is more realistic towards the deployment of pervasive IT infrastructure and services, as we feel this is how in practice businesses are likely to embrace pervasive IT. As the field of pervasive computing evolves and enterprise IT infrastructures mature around introducing pervasiveness, more fine tuning and specific detailing will be required in this model. Therefore we encourage further work in the refining and fine-tuning of this model, including cost-value propositions. In particular, we suggest a customisation of this model to specific enterprise segments.

Acknowledgements We thank Infosys Technologies Limited for supporting this research, and our colleagues Hemant Adarkar and Colin Pinto for their valuable comments on an earlier version of this paper.

References

1. Weiser M (1991) The computer for the twenty-first century. Sci Amer September 1991:94–104
2. Saha D, Mukherjee A (2003) Pervasive computing: a paradigm for the 21st century. IEEE Comp 3:25–31
3. Abowd GD, Mynatt ED (2000) Charting past, present and future research in ubiquitous computing. ACM Trans Comp-Hum Interact 7(1):29–58
4. Project Oxygen, MIT (2002) http://www.oxygen.lcs.mit.edu/. Cited 26 November 2002
5. Project Aura, Carnegie Mellon University (2002) http://www-2.cs.cmu.edu/~aura/. Cited 17 December 2002
6. Project Protolano, University of Washington portolano.cs.washington.edu/. Cited 2002
7. Project Endeavour, University of California at Berkeley (1999) http://endeavour.cs.berkeley.edu/. Cited 22 July 1999
8. Project EasyLiving, Microsoft Research-Vision Group (2003) http://research.microsoft.com/easyliving/. Cited 2003
9. Cooltown, Hewlett-Packard (2003) http://www.cooltown.com/cooltownhome/index.asp. Cited 2003
10. IBM's WebSphere Everyplace (2003) http://publib-b.boulder.ibm.com/redbooks.nsf/portals/Websphere. Cited 2003