A Taxonomy Driven Approach towards Evaluating Pervasive Computing System

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Abstract. This paper presents taxonomical classification of pervasive computing system that allows characterizing the system and helps to identify most defining performance parameters for evaluation. Tremendous efforts have been put in the related research, but there is no standard or commonly accepted model to benchmark systems and to identify direction for future research. We survey various systems published in the literature and identify their distinctive features to construct a classification scheme, and the outcome is the taxonomy of pervasive computing systems that allows us to devise strategy on how to evaluate a wide variety of these systems.

Keywords: Pervasive Computing, Taxonomy, Evaluation, Standardization, Parameters, Classification, validation.

1 Introduction

Today pervasive computing is shifting the computing paradigm toward everywhere computing. The emergence covers distributed and mobile computing, sensor networks, human computer interaction and artificial intelligence under umbrella of pervasive computing. Nearly two decades since Weiser's vision [23] was introduced, very few practical and promising systems have been deployed, and even fewer actually generated significant impact and received acceptance. As the technology is improving there is a great need of standard acceptance model to position pervasive computing systems and define directions for future research.

Researchers around the globe use evaluation techniques to benchmark their proposed work, similarly evaluation techniques are currently being used on pervasive computing and subsequently published in literature [4, 5, 9, and 19]. However, since there is no standard evaluation model, it is difficult to agree performance results presented in literature. Evaluation of pervasive computing has struggled due to the complexity, openness and diversity of technology, as a result new assessment and evaluation techniques are required to set standards. In our effort to create a comprehensive evaluation framework for pervasive computing systems, we found that it will be very effective to first categorize the systems based on some criteria and define key parameters to evaluate the systems.

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In this paper, we present the taxonomy as our first step towards designing the evaluation framework for pervasive computing system. We studied different aspects of pervasive computing and classified them into different categories. Within each aspect, we identify key parameters that can be characterized and measured. We believe this taxonomy driven approach will help in evaluating the system in term architecture, enabling technologies and application domain.

The rest of the paper is organized as follows. In section 2, we present a brief summary of all surveyed paper focusing on pervasive computing evaluation and few taxonomical classifications. In section 3, we present our taxonomy for classifying the pervasive computing system along with the key parameters. Finally in section 4, we summarized the paper and discuss about future work.

2 Related Work

Several models and schemes have been presented to evaluate and benchmark pervasive computing system. In section, we review some presentative works that address different evaluation challenges present in the domain. Gabriele suggested that traditional performance approaches are no longer applicable for pervasive computing environments due to their high QoS requirements, proactive performance tuning activities and interdependencies between user behavior and system [17]. Similarly Scott and Jennifer studied three case studies and suggested some major challenges like applicability of metrics, scale, ambiguity and unobtrusiveness for evaluation [6].

Scholtz and Consolvo presented a ubiquitous computing evaluation areas framework [9]. The goal of this framework was to develop consensus among research community for evaluating and positioning pervasive computing systems. Mark and Chris presented a comparison of quantitative and qualitative evaluation strategies and suggested a hybrid evaluation framework [5]. Jennifer and Scott suggested using unobtrusive methods to gather data by combining quantitative and qualitative methods [19]. John et al suggested selecting the metrics from scenarios that are driven by real problems rather than by the technology [4].

On the other hand, Anand Ranganathan et al divided the pervasive computing framework roughly into three layers (system support, application programming support, and end-user interface) and suggested evaluating metrics respectively [22]. Laurent and colleagues proposed a generic framework for mobility modeling in dynamic networks and argue that in future their framework can change the way for dynamic and behavior depended technology evaluation [7]. Andrea et al presented automated methods that inputs UML model of application and gives complete extended queuing network model as an output that can be evaluated with any evaluation tool [10]. Kay proposed a mathematical predictive model based on user's perception of usefulness, ease of use, social influence, trustworthiness and integration to evaluate user acceptance in pervasive computing environments [8]. Ali and colleagues presented a privacy model based on user control over private information, expressiveness of privacy policies and unobtrusiveness of privacy mechanisms [11]. Stephen introduces the Place Lab a living laboratory to study and evaluate the ubiquitous technologies in home settings [15].

The aforementioned evaluation methods are quite limited and only focused on specific areas. Our study shows that pervasive systems are highly diverse in areas such as software architecture, enabling technologies and application domain, thus it is very difficult to establish a generic and comprehensive performance evaluation framework for pervasive computing systems. Based on our observation, we conclude that as a first step toward evaluating pervasive computing system, it is necessary to examine the common characteristics and differences that separate them apart.

Taxonomy of pervasive computing systems allows us to characterize the systems and helps to identify the most defining performance parameters for evaluation. There is quite limited research on the classification of pervasive computing due to the heterogeneity of various technologies. Jeon and colleagues presented the taxonomy of ubiquitous applications and suggested the three main criteria's i.e. (subject, time and place) to classify ubiquitous applications [16]. Similarly Kista and Rajiv presented taxonomy of mobile and pervasive computing applications [12], Dennis and colleagues presented taxonomy of ubiquitous computing environments [18], Joanna and colleagues presented taxonomy of pervasive healthcare system [21], and Modahl and colleagues presented the taxonomy for a ubiquitous computing software stack called UbiqStack [20]. All these taxonomies and classification mentioned here are limited to specific domains and do not cover the complete system.

3 Taxonomy of Pervasive Computing System

After a careful study of various systems presented in literature, we analyze the distinctive features and bring together the most suitable classification. This taxonomy is by no means complete, but merely reflects on the classification scheme that best suited for the purpose of effective performance evaluations.

Based on analysis of distinctive feature of pervasive system, we have chosen seven criteria's that would exhibit vastly different characteristics and can generate the most compelling categories. The diversity of pervasive computing prevents the use of well-formed hieratical classification scheme. We take a different perspective and identify criteria's that define major divisions in operational paradigm. We first identified the differentiating parameters that can be used to categorize pervasive systems. Once the criteria and their differentiating parameters are identified, we define the categories and identify the key aspects and parameters.

Each system to be evaluated can be categorized based on one of the seven different criteria (as defined later in different subsections), and it will fall into one of the categories each time a different criterion is applied. The candidate parameters of interest for each system could be the union of the common parameters, the differentiating parameters and the key parameters associated with the category. Since there are multiple criteria employed in the taxonomy, any system can belong to multiple categories. Therefore, the set of categories the system belongs to can be used to define its character. For instance, a smart house would be considered as a centralized, assistive system that works within a single house.

The taxonomy is designed to give researchers a reference when deciding which parameters are most relevant to a particular pervasive computing system. The key aspects and parameters associated with each category are not the only parameters of interests. The specified parameters are identified that are of particular interest to each category but do not provide an exclusive list of every parameter to be evaluated.

There are common parameters that are of interest for all systems such as throughput, response time, and user acceptance. The taxonomy clarified the scope, commonalities and range of diversity of pervasive computing systems. It also generates a reference and provides guidance when researchers and implementers wish to evaluate and benchmark different systems. In next section, we present the detail description of our seven criteria presented in taxonomy.

3.1 Criteria 1: Architecture

Architecture describes the conceptual design and functional structure of all hardware and software components in pervasive systems. It provides the blueprint and operational manual during development and deployment of pervasive system. We have divided the architectural characteristics of pervasive computing system in to two major sub categories (Infrastructure and Design). Following we present the details and key evaluation parameters associated with each category.

3.1.1 Infrastructure

As one of the primary characteristic of pervasive systems is communication and computing capabilities that are integrated into environment with the possibility for a system to provide all the services from personal to global scale. We categorize systems according to the distribution of data and control, mobility of users and devices, infrastructural support of the network and the geographic span. We identify the following differentiating parameters: architectural characteristics at the system level, node-level characteristics, communication performance & cost and economical considerations that allow us to distinguish one system from another based on their differences in the network infrastructure and geographic span. Following, we define the categories under this criterion, and identify the key aspects and parameters.

CATEGORY: Network
Sub-Type: Centralized
Key Aspect:
- Resource Usage

Key Parameters:
- Software footprint
- Data storage scheme
- Scalability

Type: Distributed
Subtype: Stationary
Key aspect:
- Deployment
- Safety

Key parameters:
- Maintainability
- Security & privacy

Subtype: Grid
Key aspect:
- Resource Usage
- Safety

Key parameters:
- Process Management
- Data Management
- Data storage scheme
- Security & privacy

Subtype: Mobile (Infrastructure)
Key aspect:
- Resource Usage
- invisibility

Key parameters:
- Software footprint
- Power profile
- Data storage & manipulation
- Reliability & fault-tolerance
- Node-level characteristics & privacy

Subtype: Mobile (AdHoc)
Key aspect:
- Speed & Efficiency
- Resource Usage

- Safety
- Deployment
- Compatibility
- Invisibility

Key parameters:
- Communication performance & cost
- Data storage scheme
- Software footprint
- Node-level characteristics
- Security and privacy

CATEGORY: Geographic Span

Type: Personal-Range

Key Aspect:
- Resource Usage
- Usability
- Invisibility

Key Parameters:
- Software footprint
- Power profile
- Data storage & manipulation
- Acceptance
- Node-level characteristics

Type: Local-Range

Key Aspect:
- Safety
- Deployment

Key Parameters:
- Reliability & fault-tolerance
- Security & privacy
- Scalability

Type: Wide-range

Key Aspect:
- Resource Usage
- Deployment
- Compatibility

Key parameters:
- Power profile
- Data storage scheme
- Node-level characteristics
- Adaptability ,maintainability and self-organization

3.1.2 Design

The vision of pervasive computing is to provide user with access to computational environment anywhere anytime [23]. Thus the goal of pervasive computing system is to design software architectures that support multiple application and services in pervasive environment. The diverse nature of pervasive computing has made it difficult for software designers to adapt one common model that can meet all the requirements of pervasive computing. The major challenges that make the software design difficult are ability of software architectures to support interoperability due to various network technologies and implementations, need of user and service mobility [3]. After a careful review of different software architectures, we have identified the key differentiating parameters *(coordination, coupling, versatility and generation)* that can help to classify different software architectures used for pervasive computing. Following are the categories and the key aspect along with key parameters.

CATEGORY : Application based architecture

Key Aspects
- Modularity
- Software dynamic
- Design

Key Parameter
- Coupling And Cohesion
- Dependency between application
- Interpretability

CATEGORY : Component Oriented architecture

Key Aspects
- Modularity
- Software dynamic
- Management
- Design

- **Key Parameters**
- Component compilation
- Orchestration
- Coupling And Cohesion

CATEGORY : Service Oriented architecture

- **Key Aspects**
- Modularity
- Compatibility
- Management
- Software Dynamic
- Design

- **Key Parameters**
- Orchestration
- Runtime service generation
- Coupling And Cohesion
- Scalability
- Interoperability

CATEGORY : Agent Oriented architecture

- **Key Aspects**
- Management
- Design

- **Key Parameter**
- Choreography
- Embedded intelligence
- Autonomy
- Interpretability

3.2 Criteria 2: Application Purpose

The services and functionalities that pervasive computing systems are designed to provide are extremely diverse. The requirements and emphasis on various performance parameters are heavily dependent on their primary purposes. For example assistive services allow users to enhance and expand their communication, learning, participation, well-being, quality of life and achieve great levels of independence [21, 14]. We have define some key differentiating parameters like quality of context, reliability, fault tolerance, security, privacy and effectiveness that can be use to categories the pervasive computing applications. After analyzing the pervasive application presented in literature, we define the key differentiating parameters and categories according to their purposes. Following, we present key aspects and parameters that define each category.

CATEGORY
Assurance

Key Aspect
- Safety
- Sentience

Key Parameter
- Reliability & fault-tolerance
- Security & privacy
- Quality of Context

CATEGORY
Assistive

Key Aspect
- Usability
- Safety
- Invisibility

Key Parameter
- Reliability & fault-tolerance
- Node-level characteristics
- Security & privacy
- Modality and Effectiveness

CATEGORY
Return on Investment

Key Aspect
- Speed
- Efficiency

Key Parameter
- System performance
- Comm. performance & cost
- Economical considerations
- Data storage scheme
- Learning ability
- Efficiency

CATEGORY
Experience enhancement

Key Aspect
- Sentience
- Usability

Key Parameter
- Context characteristics
- Explicitness
- Learning ability
- Satisfaction

CATEGORY
Exploration

Key Aspect
- Sentience
- Deployment

Key Parameter
- Quality of context
- Maintainability

3.3 Criteria 3: Autonomicity

Pervasive computing systems are distributed, heterogeneous, and dynamic. Unlike computers as traditionally defined, these systems have more and diversified software and hardware components, thus making manual management and development is much more expensive. Automaticity is an aspect that describes how a pervasive computing system is initialized, how it evolves automatically to accommodate faults and failures, adjusting to users requirements, integrating new resources, and how it can identify and fend off the potential attacks. The differentiating parameter of this criterion includes the report process of new or changed requirements, number of people involved in making required changes, and level of integration between business and programmed logic. Following, we define the categories and key aspects and parameters.

CATEGORY: Static

Key Aspect
- Speed & Efficiency
- Safety

Key Parameter
- Computational performance
- I/O performance
- Reliability & Fault-tolerance

CATEGORY: Dynamic

Subtype: Self-Learning

Key Aspect
- Sentience
- Usability

Key Parameter
- Quality of context
- Knowledge representation scheme
- Error
- Learning ability
- Explicitness

Subtype: Re-Programmable

Key Aspect
- Programmability
- Deployment
- Compatibility

Key Parameter
- Ease of programming
- Maintainability
- Service & application
- Extensibility
- Backward compatibility

Subtype: Re-Configurable

Key Aspect
- Usability

Key Parameter
- Adaptability
- Ease of programming
- Self optimization

3.4 Criteria 4: Integration

Pervasive computing systems by its nature require integration of many different subsystems with very different characteristics. These subsystems include computational facilities, communication devices, mechanical or chemical sensors and actuators, smart appliances, and existing control systems. Plenty of research efforts have been spent on solving various integration issues, and different implementers have tried on different approaches. Based on the approach taken, systems usually exhibit different architectures and therefore present vastly different characteristics. After careful study of different system integration presented in literature and our own experience in building smart spaces [1,2,13], we define some differentiating parameters like maintainability, standardization, reliability, fault-tolerance, security, privacy, architectural characteristics and scalability that can be use to categories the system based on their integration methods.

CATEGORY: AdHoc Integration
Key Aspect
- Method

Key Parameter
- Designated Black-box

CATEGORY: Universal Interface
Key Aspect
- Method

Key Parameter
- Analyze data flow
- Analyze pattern
- Analyze content in pipeline

CATEGORY: Plug-In
Key Aspect
- Method

Key Parameter
- Analyze and check the performance of utilities provided in middleware.
- Pattern and efficiency of integration between application components and middleware.

3.5 Criteria 5: Interaction

In pervasive computing system, human-computer interaction and machine to machine interaction are the important components and they are becoming highly dynamic and implanted in environment. A system should adapt the interaction and presentation using various components available for interfacing based on behavior sensing, service mobility and events happening in the environment. We identify presentation as the key differentiating parameter (i.e. human to machine and machine to machines) that helps us to categorize and classify the interaction in pervasive systems. Following we define the categories under this criteria and key aspects and parameters.

CATEGORY: Human to Machine
Key Aspect
- Human Capabilities
- Preferences

Key Parameter
- Perceptual, cognitive, motor
- Interface designs
- Interaction Mode (audio, video, tangible)

CATEGORY: Machine to Machine
Key Aspect
- Interoperability

Key Parameter
- Communication protocols
- Platforms
- Computational capacities

3.6 Criteria 6: Intelligence

Pervasive computing environments are embedded with computing based devices that have ability to learn from user behaviors, their needs and preferences to adapt the environment accordingly. Ambient intelligence techniques allow these devices to help people when performing their daily living activities reactively or proactively. In our observation, we found that there are two kinds of environments, one that interacts and responds to the user behavior and preferences according to changes in user's context and behavior. The second environment is the one which personalized according to the user preferences set in his/her context (profile), and doesn't respond and adapt when the user's context or behaviors are changed. For example when a person enters to a smart room the system recognizes and personalized the environment according to his/her profile but if the person behavior is change the environment don't adapt that change. Following, we present the key aspects and parameters.

Key Aspect	**Key Parameter**
▪ Context awareness	▪ Quality of context ▪ Learning ▪ Reasoning

3.7 Criteria 7: Service Availability

The goal of pervasive computing system is to provide its user with rich set of services that are embedded in the user's physical environment and integrated seamlessly with their everyday tasks. Unlike services that are provided by internet, pervasive computing services are invisible, intelligent and invoked automatically depend on the events happening in the environment, user context or conditions that satisfy their invocation. The quality of pervasive service can be evaluated in many aspects, the key differentiating parameter that can help to categorize these services is its ubiquity. We categorize the pervasive service based on the definition of pervasive computing (i.e. any where any time). Following, we define the category under this criterion, and identify the key aspects and parameters.

CATEGORY: Any where Any -Time

Key Aspect	**Key Parameter**
▪ Discovery ▪ Location ▪ Adaptation ▪ Availability ▪ Mobility	▪ Discovery Protocol ▪ Service deployment ▪ Service composition ▪ Execution ▪ Resource availability

4 Conclusion and Future Work

There is an inherent difficulty when evaluating pervasive computing systems because of their complexity, openness and diversity of technology, therefore new standards for assessment and evaluation techniques are required. Our survey suggests that it would be extremely difficult to devise a single evaluation framework that is applicable to all systems. Instead, by first categorizing the pervasive computing system based on their distinctive features, we have established the taxonomy of pervasive computing systems. In association with each criterion, the differentiating parameters are identified to categorize various systems. Within each category, we further define their key aspects and parameters so the evaluation and comparison can be performed under a standardized and meaningful context with proper perspectives. We are currently working on a common set of scenarios that can categorize and generate the checklist to design evaluation framework that can help researcher to compare their work among other competing systems, position their work and drive future research directions. We hope that as the research community continues to move forward and new systems come into life, the taxonomy can be adjusted and expanded.

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