Hybrid Pervasive Mobile Cloud Computing: Toward Enhancing Invisibility

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Abstract

Vanishing computers into background toward invisible, distraction-free pervasive computing was envisioned by Mark Weiser which is yet remained unfulfilled. Current pervasive systems feature insufficient infrastructures to accurately perceive, infer context, tune the spaces, and prevent cyber threats. Convergence of wireless networks and cloud computing with smartphones alleviate issues and promote the Weiser’s vision. We outline Hybrid Pervasive Mobile Cloud Computing (HPMCC) as the state-of-the-art convergent paradigm comprises of pervasive artifacts, cloud resources, and smartphones. Multidimensional perception and localized elastic scalability are particular advantages of HPMCC that ensure spontaneous distraction-free human-machine interaction. Seamless application portability and multipoint data bridging are some of the open discussed issues.

Keywords: pervasive computing, mobile cloud computing, heterogeneity, invisibility, hybrid technology, cloud-based resources, localized elastic scalability, augmented smartness

1 Introduction

Efforts since 1991 toward distraction-free interaction to enhance computer use through vast variety of computers have yielded impressive achievements, yet the primary Weiser’s vision [1] of effectively hiding computers from the user remains unfulfilled. Several issues, particularly multidimensional perception, augmented smartness, and heterogeneity in current ubiquitous computing (ubicomp) model thrust invisibility by unveiling background computing and engaging peoples’ attention as the scarcest ubicomp resource.

However, recent mobile and distributed computing achievements establish a concrete ground and trigger an evolution to flourish the essence of pervasive computing: unobtrusive human-machine interaction anywhere, anytime. Staggering advances of mobile computing and wireless networking enrich perception, computing, connectivity, and mobility of Smart Mobile Devices (SMD), particularly smartphones. Among SMDs, smartphones get more intelligent and capable than ever and substitute several devices like compass, level, light sensor, and camera. Similarly, cloud computing, as the latest distributed computing accomplishment, delivers infinite rich on-demand computing resources to people —similar to the utilities. But, SMD devices rich in smartness and mobility suffer from resource poverty and the cloud servers rich in computing resources lack mobility. Whereas, Weiser highlighted the real power of pervasive computing comes from the interaction varied devices. Therefore, Mobile Cloud Computing (MCC) technology comprised of heterogeneous domain of mobile computing, cloud computing, and networking [2] can enrich pervasive computing.

After identifying the key issues in pervasive computing through the literature, and examining the technological achievements and today’s trend, we discover that amalgam of mobile, cloud, and pervasive computing likely advances the Weiser’s vision of invisible pervasive computing. Thus, we disclose Hybrid Pervasive Mobile Cloud Computing (HPMCC) as a convergent paradigm that heralds a new era for pervasive computing and deemed could significantly enhance ubicomp systems, expose them to unexplored realms, and insensibly bring smartness to the human. People in the near future, will unconsciously divulge themselves in smart spaces and pay as they use.
We highlight the need for advancement in current ubicomp model by describing several key issues, especially multidimensional perception, elastic scalability, and heterogeneity. We explain how amalgam of mobile, cloud, and pervasive computing in HPMCC can alleviate shortcomings of current ubicomp systems toward enhancing invisibility. Several open issues that grant polygonal research area are described.

2 Smart Mobile Devices

The rapid evolution of ordinary mobile devices to the SMDs with envision of cognitive ability as the next evolutionary step heralds a new era of ubicomp. Presently, the multiple roles SMDs, especially smartphones play in ubicomp [3] galvanize the research community to sketch the boundaries to embrace them. Operating as a context collector via multiple sensors, acting as an information service delivery point, working as one-hop relay to integrate distant servers and embedded artifacts, and the vision of intelligently combining perceiving context from heterogeneous sources are particular SMDs’ roles in the near future. High quality camera, microphone, and various digital sensors (e.g., gyro and compass) enable SMDs, especially smartphones to comprehensively capture contextual and social information, while their ever-augmenting computing resources, big screen, and varied networking technologies empower them to conveniently interact with people and pervasive objects. Recent efforts [4, 5] and technological advances enable smartphones to host varied computations toward ubiquitous service providers. In [4] researchers investigate and propose a framework for web service provisioning on SMDs. The authors in [5] propose a market-oriented architecture by which prefabricated web service can be hosted and executed on SMD on behalf of nearby resource-constraint SMDs.

Thus, perception and smartness surge by acquiring and processing contextual information; the more context interpretation, the richer human-machine interaction. Multitude of non-smart environments such as an old car’s cabin can become smart exploiting the perceptional capabilities of low-cost SMDs. Although SMDs, especially smartphones as truly pervasive computers conveniently see, hear, and sense changes in surrounding objects, their perception is limited to a small neighboring area, and their computing power and energy are faint compared with desktop machines. A feasible solution to these shortcomings is to leverage rich cloud computing resources.

3 Mobile Cloud Computing

Cloud computing is the most profound distributed computing technology rapidly penetrating in various aspects of humans’ life. It aims to conveniently enable ubiquitous, on-demand access to a unified cluster of computing resources (e.g., processing, storage, and network) that can be elastically provisioned and released with least investment, complexity, and interaction [6]. People consume rich computing and storage resources in cloud, pay as they use —similar to electricity and water—, and access them anywhere, anytime, from any Internet-connected device without upfront investment and provisioning. For example, users store unlimited personal photos, songs, and documents in the cloud and access them regardless of time, place, and interacting device. Cloud-based mobile augmentation approaches [7] by employing clouds to augment resource deficiency of SMDs (particularly smartphones) breeds Mobile Cloud Computing (MCC) paradigm.

MCC is a rich mobile computing technology that leverages unified elastic resources of varied clouds and network technologies towards unrestricted functionality, storage, and mobility for a multitude of mobile devices anywhere, anytime through the channel of Ethernet or Internet regardless of heterogeneous environments and platforms based on the pay-as-you-use principle [2]. MCC envisions conserving user attention toward successful pervasive computing by reducing or omitting interaction’s distractions, especially erratic performance, inaccurate results, and out-of-context interaction using plentiful computing resources. MCC is a horizontal heterogeneous computing paradigm comprised of three inhomogeneous computing domains of mobile computing, cloud computing, and networking (wired and wireless) [8] which provides additional advantages to MCC users compared to mobile computing and cloud computing [9].

Researchers employ various design patterns in MCC to build and optimize cloud resources for SMDs such as proposing frameworks for distributed application processing in SMDs [10]. For instance, Clonecloud [11] aims to conserve computing resources and battery of mobile devices by offloading intensive computation tasks from mobile device to the clone of mobile OS in the distant cloud (Figure 1a). However, runtime application partitioning on SMD, cloning and migrating the OS through the limited wireless bandwidth to a distant resource, and VM deployment and management for application processing in cloud-computing
infrastructure imposes large overhead on the mobile device and wireless network, and prolongs the application execution time [12, 13]. In Cloudlet [14] a lightweight clone of mobile application (code and data state) is offloaded to proximate immobile computing entities, able to perform computation on behalf of resource-constraint smartphones (Figure 1b). To neutralize the impact of latency on interaction response time, the authors build localized resources and assume mobile OSs exists in the Cloudlet. Hyrax [5, 15] aims to reduce the impact of latency and mobile-cloud heterogeneity by building a cloud of proximate mobile computing entities being able to execute intensive tasks in distributed manner (Figure 1c). However, each of these remote cannot individually fulfill computing requirement of pervasive systems due to their particular characteristics (e.g., distance and scalability). Recently, researchers in [16] introduce a hybrid infrastructure comprises of three near and far resource levels, namely public clouds, Mobile Network Operators (MNOs), and MNO’s authorized dealers to alleviate shortcomings of single-tier cloud resources. Similarly, authors in MAPCloud [17] introduce a hybrid 2-tier cloud infrastructure comprises of distant clouds and nearby Cloudlet that noticeably saves power, reduces latency, and increases scalability compared to single-tier distant clouds.

4 Hybrid Pervasive Mobile Cloud Computing

HPMCC is a converged computing paradigm comprises of pervasive, mobile, and cloud computing technologies to reduce or eliminate distractions originated from inadequate sensing, computing, connectivity, and security -to name a few- towards distraction-free interaction. Current pervasive systems feature weak and insufficient infrastructures and mechanisms to accurately perceive changes, compute and infer context information, provide localized on-demand scalability, tune the spaces, maintain seamless connectivity, and protect the system from security and privacy threats [18, 19]. They exploit resources- and energy-constraint computing entities and perform in a limited geographical realm.

HPMCC presents a novel hybrid multi-tier infrastructure (Figure 1d) consisting of near/far mobile and fixed heterogeneous computing entities, particularly distant clouds, nearby desktops, and crowd of proximate SMDs [7], especially modern smartphones to constitute a rich ubiquitous remote infrastructures. Rich computing resources of distant public clouds is shown in Figure 1a. Although it provides infinite elastic resources and can accommodate context from varied context-generators, long distance between service consumer and cloud inhibits localized scalability and increases latency. Figure 1b illustrates desktop computer or cluster of computers in vicinity that can perform moderately-intensive tasks on behalf of resource-constraint artifacts. Low propagation delay due to short distance between service consumer and provider enhance utilization time while limitations in resources encumber scalability. Figure 1c shows proximity of service provider SMDs and service consumers. Sensing capabilities, computing ability, and ubiquity of SMDs enhance perception and smartness in pervasive systems by alleviating localized scalability, whereas their computing and energy resources are restraint compared to other resource types.

The hybrid multi-tier infrastructure inherits benefits of different types of infrastructures to deliver high perception, smartness, and localized scalability, to name a few. Therefore, HPMCC could alleviate majority of pervasive computing problems, particularly context-awareness, smartness, and localized scalability and remarkably unleash the power of pervasive computing. Necessary resources in HPMCC are allocated to a specific task considering its resource and QoS requirements. For instance, a security-intensive heavy task is offloaded to the secure distant cloud, whereas a latency-sensitive lightweight computation is migrated to a nearby SMDs or desktops. Pervasive systems conveniently utilize multidimensional perception via pervasive economic perspicacious SMDs, augmented smart spaces utilizing infinite cloud resources, and localized scalability using numerous cloud-connected SMDs toward anytime, anywhere, any-device computing and interaction.

5 How HPMCC Enhances Invisibility?

Invisibility as a vital thrust of pervasive computing aims to automatically meet user expectations and completely disappear ubicomp technologies from users’ consciousness. Debashis Saha and Amitava Mukherjee [18] state “to meet user expectations continuously, however, the environment and the objects in it must be able to tune themselves without distracting user at a conscious level”. Nevertheless, several issues, listed in Table 1 and described as follows, should be alleviated to enable the automatic spontaneous tuning of the environment and involved artifacts. The Table presents invisibility issues, requirements to alleviate them,
5.1 Multidimensional Perception

Perception or context awareness as the core requirement of pervasive systems highly impacts on invisibility. An effective perception requires precise and continuous perceiving of changes in surrounding spaces, including human behaviors, which lacks in most of present ubicomp systems. Acquiring multidimensional context information from various sources, including large number of individual sensors increases monetary cost of owning sensors, raises implementation and maintenance complexity, and stems several challenges. Communicating with multiple devices that support heterogeneous technologies such as Infrared, Bluetooth, and 3G beside understanding and integrating heterogeneous information from various context resources are challenging tasks that demand well-established interlaced systems.

Multidimensional perception will become a reality in HPMCC where collected context and cognitive information from smartphone pervasive devices can be incorporated with cloud-stored information generated by third parties (e.g., government agencies and healthcare organizations). Such comprehensive context information can be used in ubicomp systems to accurately anticipate people’s intent and make timely context-sensitive decisions that meet their expectations to have Rich Mobile Applications (RMAs) [20]. For instance, the facial context collected by smartphone and illness symptoms acquired by healthcare pervasive device can be combined with cloud-stored medical data provided by the healthcare agencies to effectively adjust the room’s temperature before the occupant enters home. FoneAstra [21] is a mobile phone-based perceiving system to monitor vaccine temperature. It stores sensed context into a central server to be accessed by authorized supervisors. However, it relies on limited context collection capabilities of mobile devices and fails to acquire secondary context information from peripheral context-generating entities, if any. Moreover, utilizing a central server inhibits scalability, impose ownership and management cost, and threaten system security and reliability. Deploying HPMCC in such pervasive systems enables low-cost multidimensional perception from different resources and scalable computing in large scale deployment.

Furthermore, in HPMCC, smartphones as a communication gateway are able to communicate and transfer data between various entities, including sensing artifacts, processing resource, and space tuning infrastructures. HPMCC can exploit cloud interoperability solutions such as RASIC [22] to integrate varied computing and sensing entities, and enable acquisition and processing of information from dissimilar entities. RASIC is
Table 1: Invisibility issues in current pervasive systems that can be alleviated by Hybrid Pervasive Mobile Cloud Computing (HPMCC)

<table>
<thead>
<tr>
<th>Invisibility Issue</th>
<th>Requirements</th>
<th>HPMCC Opportunity</th>
<th>HPMCC Open Issues</th>
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<tbody>
<tr>
<td>Multidimensional Perception</td>
<td>- Multiple context sources</td>
<td>- Embedded sensors</td>
<td>- Seamless context integration</td>
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<td></td>
<td>- Precise context acquisition tools and programs</td>
<td>- Smartphone sensing power</td>
<td>- Seamless interoperability</td>
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<td>- User intent’s anticipation</td>
<td>- Cloud-stored context</td>
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<td></td>
<td></td>
<td>- Smartphones as gateway</td>
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<tr>
<td>Augmented Smartness</td>
<td>- Giant computation resources</td>
<td>- Infinite Cloud-assisted smartphone computation resource.</td>
<td>- Task offloading</td>
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<td></td>
<td>- Timely and efficient context management</td>
<td>- Timely and efficient context smartphone computation</td>
<td>- Self-optimizing</td>
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<td></td>
<td>- Computation offloading</td>
<td>- Self-healing</td>
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<td>- Context validity and reliability</td>
<td>- Self-protection</td>
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<td>Seamless Application Mobility</td>
<td>- Seamless communication</td>
<td>- Application offloading</td>
<td>- Seamless connectivity</td>
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<td></td>
<td>- Seamless computation</td>
<td>- Cloud-based hybrid apps</td>
<td>- Seamless interoperability &amp; portability</td>
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<td>- Adaptable application</td>
<td>- Content adaptation in cloud</td>
<td>- Cloud-based hybrid app development framework</td>
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<td>- Platform-neutral apps</td>
<td>- Infinite cloud storage</td>
<td>- Lightweight virtualization</td>
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<td></td>
<td>- Virtual environment</td>
<td>- Adaptive offloading</td>
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<td>Elastic Scalability</td>
<td>- Localized scalability</td>
<td>- Low-cost numerous cloud-based smartphones</td>
<td>- Self-management</td>
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<td>- Low latency</td>
<td>- Computing on nearby Cloudlet or crowd of proximate smartphones</td>
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<td>- Scalable, elastic computing resources</td>
<td>- Elastic cloud resources</td>
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<td>- Multi-purpose smartphones</td>
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<td>Security, Privacy, &amp; Data safety</td>
<td>- Enhanced security</td>
<td>- MNO supervision and control</td>
<td>- Lightweight security algorithm</td>
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<td>- Increased privacy</td>
<td>- Security provision on smartphone and cloud</td>
<td>- Trust establishment</td>
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<td>- Trust management</td>
<td>- Data protection in cloud</td>
<td>- Self-protection</td>
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<td>- Improved data safety</td>
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<td>- Self-healing</td>
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<td>- Fault tolerance &amp; handling</td>
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<td>Heterogeneity</td>
<td>- Mask heterogeneity</td>
<td>- Platform-independent cloud-based pervasive applications</td>
<td>- Cloud interoperability</td>
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<td>- Mask uneven condition</td>
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<td>- Integrity &amp; management of apps &amp; databases</td>
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<td>- Multipoint data bridging</td>
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<td>- Platform-neutral models &amp; programming languages</td>
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<td>- Open standard</td>
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<td>- Self configuration</td>
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a SOA-based architecture for heterogeneous clouds to enable semantic interoperability among clouds. The authors argue that utilizing SOA-based design towards a common API standard for cloud can ease content migration across heterogeneous clouds and reduce the cost of porting data and application from one cloud to another. However, seamless integration of multidimensional context information needs future efforts.

### 5.2 Augmented Smartness

In pervasive computing systems, accommodating computation in the spaces and turning them smart is crucial need. But, major present ubicomp spaces lack sufficient computing elements due to the high cost of embedded computers, lack of comprehensive context, and limited weak computing resources [19]. Hence, timely environment tuning is inhibited and systems fail to fulfill user expectations leading to invisibility degradation. Augmented context processing and interpreting devices are necessary to derive instantaneous conclusions and tune the space in reflection to the immediate user’s decision change. Context processing in smart pervasive spaces relies on artificial intelligence techniques, particularly planning, reasoning, and machine learning that are intensive tasks. They consume large computation resources and take long time...
to complete, which decrease system performance and interaction quality. Therefore, insufficient proximate computation resources encumber human-machine unobtrusive interaction.

HPMCC aims to augment computation capabilities of smart spaces by exploiting rich hybrid computing resources. Figure 2 illustrates an exemplary scenario to demonstrate how HPMCC augmented smartness can save David’s life when he experienced a heart attack in a park in town. In the future, HPMCC-connected mobile health devices (e.g., Defibrillator) can be augmented by exploiting multidimensional context information to more effectively trigger precautionary actions that enhance the system’s reliability toward invisible technology. Resource-intensive computation tasks can be offloaded to the rich remote resources for execution on behalf of the resource-constraint pervasive artifacts [11]. While human-machine interaction continues, the offloaded tasks are completed and results are sent back to the artifact to deliver a distraction-less interaction to the people. Despite of remarkable yields in offloading methods, several critical issues, particularly deciding whether to offload intensive tasks and specifying appropriate time, place, and method for offloading in dynamic ubicomp environments need to be addressed. Researchers in Intel [23] endeavor to efficiently offload heavy computation (extracting complex context and activity information from sensed data) to the cloud for execution on behalf of the resource-constraint pervasive artifacts. But, long WAN latency of utilizing distant cloud resources for various types of computation degrades the system efficiency.

Additionally, smartness in HPMCC is unpredictable and bursty due to the excessive dynamism of the environment that intensify uneven conditioning; when a crowd of people enter a space, their cloud-connected smartphones can sharply amplify smartness by empowering sensing and computing ability for time being; such invisibility continuously shrinks when people leaving the space. To facilitate system administration and mitigate the impact of such challenging dynamism, self-monitoring, -adapting, and -optimizing techniques in imminent pervasive systems are inevitable.

5.3 Seamless Application Mobility

Seamless application mobility is a challenging task in pervasive computing. It is the ability to continuously and consistently deliver data and application to the consumers anywhere anytime from any computing and interacting device. Fulfilling such expectation demands seamless communication and computing among multitude of heterogeneous technologies and devices. Mobilizing computation in such fragmented domain needs integration of varied devices and technologies to realize cross-platform cross-device and adaptable applications, which are challenging in spite of current advances. Imminent pervasive systems will likely hide dissimilarities of computing and communication technologies in background and enhance service invisibility. For instance, people watching a soccer match in a coffee shop by leveraging vehicular cloud computing [24] can maintain vehicular multimedia system on the way home, continue watching the game using smartphone in elevator, and see the rest in bed via home theater system.
HPMCC envisions integrating large number of network technologies and computation devices (e.g., embedded systems, smartphones, desktops, and clouds) towards enriched invisibility. In the cloud, virtual execution environments on top of infinite unified heterogeneous CPU, memory, and storage deliver unrestricted computing to ubicomp systems. In client side, computation offloading processes and cloud-based mobile applications maintain cloud’s virtual execution environment to execute heavy computations on dissimilar infrastructures and platforms to conserve native resources. Cloud resources facilitate continuous rich computing on the go regardless of SMDs’ resources and battery deficiency that helps application developers to build applications for all types of devices. Moreover, executing pervasive applications, partially or entirely, in the cloud and storing data inside the cloud reduce their dependency to the mobile and pervasive devices and promote code and data mobility. For instance, iCloud enables users to access and modify multimedia data and tasks (e.g., editing images and music files) in the cloud from different iOS computing devices —mobile or fixed. However, accessing content from non-iOS devices is restricted in iCloud. Enabling device-independent access to cloud-stored content is a lacking feature of current systems like iCloud.

Nevertheless, seamless connectivity across heterogeneous systems, understanding geographical information resources, and exchanging data between/across two or more heterogeneous systems are issues in cloud utilization process that demand data interoperation and portability. Frameworks to build cloud-based applications similar to [25] beside low-footprint virtualization methods unleash the power of HPMCC in future. Also, configuring and optimizing a multitude of devices and technologies from various vendors are complex tasks which demand great efforts and skills. Failure in seamless communication and computation among various devices surprises people and brings background computing to the foreground. Therefore, automatic systems to alleviate resource management and maintenance can hide ubicomp technology from users.

5.4 Localized Elastic Scalability

In the near future, pervasive computing environments will experience rapid proliferation of users, applications, devices, contexts, communications, and human-machine and machine-machine interactions. Multiplicity of applications, sensing resources, and devices enhances reliability of context acquisition and inference processes in smart spaces towards invisible computing and interaction. But, fulfilling scalability primitives such as establishing timely communication between abundant entities, accurate local context processing and environment tuning with at least delay, efficient application deployment and updating on huge number of devices, and spontaneous fulfillment of ever-increasing people expectations is challenging. It needs continuous sensing of changes in near spaces, frequent forecasting of users’ requirements and preferences, and optimal provisioning of proximate computing infrastructures, which levy huge monitoring, establishment, and maintenance overhead and cost on ubicomp systems. For example, in case of manual infrastructure provisioning, surplus infrastructures are needless when the system’s load shrinks down leads to decreasing the infrastructure utilization ratio and energy efficiency in system. Similarly, when user leaves the space, its computational tasks also need to migrate along.

HPMCC deemed could provide a platform to enable localized elastic scalability by leveraging hybrid infrastructures, including comparatively low-cost computing resources of numerous nearby SMDs, cloudlets, and distant cloud which requires. Allocating hybrid resources to the varied service consumers requires agile cloud service selection [26] approaches like [27, 28]. Localized elastic scalability refers to the mechanism of unforeseen utilization of nearby infrastructures that can be shrunk up and down on-demand. Users can access unlimited amount of resources on payment, when hybrid infrastructures are seamlessly integrated to the pervasive environment. Efforts such as Hyrax, MOMCC, and Cloudlet can increase localized elastic resources and decrease the impact of latency. Hyrax and MOMCC distributes intensive computing tasks of a resource-constraint smartphone among a crowd of nearby smartphones. In Cloudlet, applications are offloaded to the localized powerful computer(s) for execution. However, obtaining crisp response is a fundamental issue, especially in wireless communication that requires revolutionary advancements to significantly reduce latency.

Moreover, surging growth of entities in HPMCC breeds several challenges. The increasing number of very large scale geographically distributed data warehouses and the non-similarity of data structures complicate data management. Integrating huge distributed data and providing virtually unified storage for mobile users is becoming more complex with the ever increasing heterogeneity. Determining and allocating suitable computing resources (e.g., embedded device, SMDs, and cloud) to the heavy tasks is another issue that requires future advancements. Although convergence of heterogeneous computing and sensing devices is beneficial and enhance the system scalability, tuning a smart environment according to huge context (sometimes contrary context) to meet expectations of large number of people is a non-trivial task. Providing a
mechanism to resolve appropriation demands from several users in the absence of self-managing systems is another challenge.

5.5 Security, privacy and trust

Security and privacy are necessary in all aspects of pervasive computing, including hardware, operating systems, database, context (especially asserted information by third parties), interaction, and communication (especially wireless). In the absence of the accurate and robust security provisions, threats such as falsifying context information, attacking database, and shutting down perceiving devices can violate system security and user privacy. People need certain degree of protection against their confidential, clandestine data, though their behaviors in social websites such as Facebook and Tweeter advocate that large community of users partially forfeit their privacy. In pervasive systems, several unsafe activities such as interacting with the system via unreliable public devices, relying on the context information with insufficient knowledge of issuing sources, performing insecure communications, and storing data in vulnerable storages can potentially endanger user’s security and privacy. Storing data in mobile pervasive devices decreases data safety due to the risks of device malfunction, physical damage, robbery, and loss of mobile devices. Hence, such uncertainty and vulnerability lead to distrust in the system and consequently expose hidden computing processes to the user, which degrades system invisibility.

HPMCC is connoted to enhance security, privacy, and data safety in pervasive computing; infinite computing resources enable performing intensive security algorithms that enhance overall system’s security. Mobile network operators can add a value-added service by supervising and controlling —relatively tight—the communication to mitigate cyber threats. Similarly, privacy is increased when we use smartphones as information reception points and interaction devices instead of unreliable public machines. Furthermore, data can be stored in a secure cloud storage rather than insecure embedded devices or mobile computers to protect data against several safety breaches. Trust in ubicomp systems is inhibited by inaccurate and unreliable sensing of the environments, mainly because of malfunctioning sensors, falsified or corrupted context, and inaccurate sensing time. In HPMCC, sensing accuracy can be enhanced via leveraging multitude of SMDs and giant computing resources. SMDs can acquire great amount of sensing context and perform light pre-processing to enhance integrity and reliability of collected context. HPMCC can leverage cloud resources to verify and validate context accuracy against a warehouse of momently sensed context from wealth of sensing artifacts.

Nevertheless, lightweight robust mechanisms to efficiently deploy security and privacy in HPMCC are essential in the wireless environment. Despite of noticeable advancements in trust establishment, users still concern about the clouds’ security and privacy. Addressing such crucial needs by employing a novel lightweight security algorithm in mobile side and a set of robust security mechanisms in cloud demand future efforts. Methods such as construct encryption data management scheme using bucket ID to secure data [29], beside developing self-healing and self-protective mechanisms in HPMCC can significantly enhance security, privacy, and trust.

5.6 Heterogeneity

Heterogeneity in ubicomp is the co-existence of varied types of fragmentation, particularly hardware, OSs, applications, networking technologies, energy characteristics, and screen sizes. Heterogeneous infrastructures in varied spaces create dissimilar perception and smartness, diversify user interaction quality, and consequently distract human-machine interaction. The most challenging heterogeneity consequence in ubicomp is the intensified complexity of developing cross-platform cross-device applications. Masking such diversifications and uneven conditions improves invisibility in ubicomp and enriches user experience.

HPMCC is capable of shrinking application dependency to specific platform and device by facilitating development of platform-independent cloud-based applications. In cloud-based hybrid applications [25], the user interface and native components (codes rely on device’s features such as camera)—which are small fraction of the whole code—are usually executing inside the client devices, while complex components (e.g., prediction and inference functions in ubicomp) are offloaded to the cloud for execution. Upon successful cloud-side execution, the results are returned back to the mobile for integrating to the native mobile components. Hence, developers can implement single version of each cloud-component and utilize it in multitude of devices with no/minor modification leading to enhanced application development.
Although HPMCC heterogeneity is intensified in convergence of heterogeneous domains of mobile, cloud, and ubicomp, it creates benefits to the ubicomp systems and users. Employing multitude of varied devices, communication technologies, and ubicomp services with enforcing standards increase flexibility and enhance computing performance in pervasive spaces. Furthermore, HPMCC-users can leverage cloud-based applications to conveniently move among heterogeneous devices, particularly cloud-based TV, PC, and smartphone to continue their task regardless of underlying system architectures and background process.

However, underlying heterogeneity among varied hybrid computing infrastructures in HPMCC stems several challenges that demand future researches. Rapid growth in digital contents and increasing dependency of ubicomp systems and users to the remote infrastructures intensify content management in pervasive environments. Code and data are distributed among heterogeneous smartphones, desktops, and cloud resources via different communication technologies for execution. Although executing complex applications and accessing big data are facilitated, locating, accessing, updating, and synchronizing huge volume of highly distributed contents are difficult. Similarly, connecting heterogeneous wired and wireless systems, understanding geographical information resources, and exchanging data between/across two or more heterogeneous systems are the main issues in HPMCC systems, which demand data interoperation techniques in the absence of open standards. The inward heterogeneous architectures and data structures of mobile devices and cloud systems with different APIs can exemplify the intensity of multipoint data bridging challenge that obligate self-configuring mechanisms in HPMCC.

6 Conclusions

In spite of significant achievements towards Weiser’s vision of distraction-free interaction, still invisibility is unfulfilled. Today’s trend is to augment pervasive systems by amalgam of technological advancements in cloud and mobile computing (particularly smartphones and wireless networks). We disclose such trend as Hybrid Pervasive Mobile Cloud Computing (HPMCC) paradigm. We trust that perspicacious smartphones and infinite rich multi-tier computing resources expose pervasive systems to unexplored realms, magnify context-awareness and smartness, improve scalability, and alleviate security and heterogeneity. However, several challenges, particularly autonomic pervasive computing, lightweight protocols, and reducing latency require future efforts to fully unleash the power of HPMCC.

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References


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