Journal of Network and Computer Applications 115 (2018) 70–85

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

journal homepage: www.elsevier.com/locate/jnca

Mobile cloud computing: Challenges and future research directions

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ARTICLE INFO

Keywords:
Cloud computing
Cloud services
Mobile cloud computing
Mobile services
Smartphones

ABSTRACT

Mobile cloud computing promises several benefits such as extra battery life and storage, scalability, and reliability. However, there are still challenges that must be addressed in order to enable the ubiquitous deployment and adoption of mobile cloud computing. Some of these challenges include security, privacy and trust, bandwidth and data transfer, data management and synchronization, energy efficiency, and heterogeneity. We present a thorough overview of mobile cloud computing and differentiate it from traditional cloud computing. Also presented here is a generic architecture that evaluates 30 recently proposed mobile cloud computing research architectures (i.e., published since 2010). This is achieved by utilizing a set of assessment criteria. Finally, we discuss future research challenges that require further attention.

1. Introduction

Over the past few years, mobile cloud computing has been changing the landscape of traditional mobile computing by providing on-demand, self-service, measured, elastic, and broad access mobile services. Mobile cloud computing devices such as smartphones and tablets are becoming a significant part of our modern and virtual lifestyle. For example, the number of smartphone and tablet shipments has grown exponentially and by 2016 reached 1.9 billion units globally according to the International Data Corporation (IDC) Worldwide Quarterly Smart Connected Device Tracker (Meulen, 2016). The mobile cloud computing paradigm emerged as a way to combine the benefits of mobile computing (Dinh et al., 2011) with those of cloud computing (Fernando et al., 2013) in order to better employ datacenters' computing capabilities and deliver them as mobile services. For mobile computing, mobile devices are designed with limited hardware, software, and communication capabilities with mobility being the major criteria. Regarding cloud computing, massive computing capabilities are delivered as services using virtualization and service oriented techniques to reduce cost, improve performance, or allow remote access. Mobile cloud computing enables large and powerful computing capabilities to be delivered as services. This allows mobile devices with limited resources to perform complex computations that require more powerful computing resources.

Although mobile cloud computing can offer several important benefits such as extended battery life and higher storage, scalability, and reliability, several key challenges continue to be a major impediment to mobile cloud computing adoption. These challenges include security and privacy, bandwidth and data transfer, data management and synchronization, energy efficiency, and heterogeneity that need to be resolved. We also need to address such challenges in order to enable mobile cloud service consumers to enjoy the advantages of mobile cloud computing. Traditional cloud computing approaches might not be adequate for the current mobile cloud computing environment due to their limited connectivity, energy constraints, and distributed nature (Fernando et al., 2013; Dinh et al., 2011; Kovachev et al., 2011).

In this study, we compare and contrast traditional cloud computing with mobile cloud computing. We compare 26 recent surveys (i.e., published from 2010 to the present day) on mobile cloud computing by highlighting their focus; the components of the proposed architecture for mobile cloud computing if there is any, expressing their contributions, identifying the analysis technique used to determine research challenges for mobile cloud computing and describe these challenges. Moreover, we propose a generic architecture that covers all layers of mobile cloud computing to identify the relevant issues. In particular, we compare 30 recent representative mobile cloud computing research architectures (i.e., since 2010) using our proposed architecture. To study these research architectures, we identify several assessment criteria. As well, we provide a holistic view of the current status of mobile cloud computing by presenting a quantitative analysis (i.e., where statistical information about mobile cloud computing architectures is used), and benchmark comparison to determine research challenges for

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https://doi.org/10.1016/j.jnca.2018.04.018
Received 1 January 2018; Received in revised form 9 April 2018; Accepted 27 April 2018
Available online 02 May 2018
1084-8045/

mobile cloud computing which represent the main contribution of our work. Furthermore, we also discuss future research challenges for mobile cloud computing based on the comparison of the recent representative mobile cloud computing research architectures.

The rest of the article is organized as follows. In Section 2 we present the related work and compares 26 recent surveys on mobile cloud computing. In Section 3, we present some background information and document a comparison between traditional cloud computing and mobile cloud computing. In Section 4, we propose a generic architecture for mobile cloud computing and identify a set of dimensions which are used for comparing recent representative mobile cloud computing research architectures. Section 5 presents our survey and evaluation of 30 recent representative mobile cloud computing research architectures. In Section 6, we discuss critical research challenges and propose future research directions. In Section 7, we make some concluding remarks and point out the implication of this research.

2. Related work

Mobile cloud computing has been an active research area in recent years and several surveys have been published on this topic. (Chetan et al., 2010), conducted one of the first surveys that focus on mobile cloud computing issues. This survey presents an overview about how mobile cloud computing works, discusses some problems and possible solutions related to mobile cloud computing, and outlines the advantages of mobile cloud computing. Furthermore, the survey presents some research issues that needs to be addressed such as absence of standards, access schemes, security, and the need for elastic mobile applications (Dinh et al., 2011). present an overview of mobile cloud computing definitions, architecture, and benefits. The survey proposes an architecture of mobile cloud computing which consists of five components including mobile users, network operators, Internet service providers, application service providers, and datacenter owners. Apart from a discussion of the issues, existing solutions and approaches of mobile cloud computing, the survey provides future research directions in mobile cloud computing with a focus on low bandwidth, network access management, quality of service, pricing, standard interface, and service convergence (Kovachev et al., 2011). compare several mobile application models that are compatible with cloud computing according to a set of criteria including the enabling middle-ware, cost model, programming abstraction, solution generality, implementation complexity, static and dynamic adaptation, network load, and scalability. Based on the comparison, the authors discuss many research challenges including programming abstraction, cost model, adaptation, cloud integration, and trust, security and privacy (Cox, 2011). presents a brief overview of mobile cloud computing devices, trends, issues, and enabling technologies. The author argues that in a few years, there will be one trillion cloud-ready devices such as smart phones, tablets, and WiFi sensors. The most challenging issues present in this work include device resource poverty, latency, bandwidth, and security.

Bahl et al. (2012) provide a brief study on the combination of mobile and cloud computing, and argue for the need to offload tasks of mobile applications. In their study, the authors propose a mobile cloud computing architecture which consists of four components, including mobile devices, wireless core, WiFi AP, and Regional Data Centers (RDC). Moreover, the authors compare different programming models (e.g., CloneCloud (Chun and Maniatis, 2009), MAUI (Cuervo et al., 2010), Odessa (Ra et al., 2011), and Orleans (Bykov et al., 2011)) for mobile cloud computing (Qi and Gani, 2012). review mobile cloud computing characteristics and architectures. Also, the authors propose a mobile cloud computing architecture comprising four components; mobile devices, wireless access point and mobile tower, servers and VMs. Furthermore, the authors provide a comparison of four mobile cloud computing architectures including CloneCloud system architecture (Chun and Maniatis, 2009), AlfredO system architecture (Giurgiu et al., 2009), and CloudLet (Satyanarayanan et al., 2009). It is contended that more research is required on data delivery, task division, and better service provisioning. (Fernando et al., 2013), present a survey on mobile cloud computing and provide a taxonomy based on some key issues such as operational issues, end user and service levels, security, context awareness, and data management. In addition, the survey proposes a mobile cloud computing architecture which consists of five components including privacy and security manager, context manager, resource handler, cost manger, and job handler. Furthermore, the study provides an overview of cost models in mobile clouds and a comparison of connection protocols used in mobile clouds. Based on the results of the comparisons, the authors think that the challenging research issues in mobile cloud computing include operational, presentation and usability, service level, privacy and security, context awareness, and data management. (Rahimi et al., 2014), present a survey on mobile cloud computing and provide a comparison of 16 mobile could computing systems based on a set of criteria including objectives, used technology, wireless connectivity type, and security and privacy. The survey discuss some research open issues such as power and execution time efficiency, communication bandwidth efficiency, and security and privacy.

More recently (Stergiou and Psannis, 2017), in their more generic survey cover the latest advances in mobile cloud computing and Internet of Things (IoT) concerning big data applications. There is an emphasis on the main features and trade-offs concerning IoT and mobile cloud computing. Furthermore, the survey discusses research challenges such as security, connectivity, performance, latency, and privacy (Wang et al., 2015). look at existing infrastructure-based mobile cloud computing applications in their analysis. They categorizes mobile cloud computing into four categories namely i) crowdsourcing applications, ii) collective sensing applications (e.g., traffic monitoring, social networking, and healthcare), iii) location-based applications, and iv) augmented reality and mobile gaming applications. Furthermore, the research challenges that emerge in their paper include code computation (offloading), task-oriented mobile services, elasticity and scalability, security, and cloud service pricing. (Abdo and Demerjian, 2017), investigate mobile cloud computing architectures and applications. In particular, the survey proposes a mobile cloud computing architecture characterized by four components specifically E-UTRAN, mobile operator's core network, internet, and cloud service provider's network. Moreover, their study presents a comparison of four mobile cloud computing architectures' performance against non-quantifiable requirements which include privacy, mobility, scalability, and multicast capability. In addition, the survey compares 14 mobile cloud computing applications performance when deployed across different mobile cloud architectures. The application performance is measured using quantifiable metrics such as cost, delay, and power consumption.

Some surveys on mobile cloud computing focus on specific aspects such as security and energy efficiency. For example (Alizadeh et al., 2016), comprehensively focus on authentication methods in mobile cloud computing. Their study proposes four mobile cloud computing architecture models including i) Distant immobile cloud, ii) Proximate immobile computing, iii) Proximate mobile computing, and iv) Hybrid computing. Specifically, these authors compare authentication methods used in mobile cloud computing with the ones used in traditional cloud computing. The survey also evaluates existing authentication methods using five metrics namely; usability, efficiency, security and robustness, privacy, and adaptability to mobile cloud computing environments. Furthermore, the challenges they found requiring further analysis concerning authentication in mobile cloud computing include heterogeneous infrastructure, seamless handover, identity privacy, and resource scheduling. (Gai et al., 2016a), explore intrusion detection techniques for mobile cloud computing in heterogeneous 5G. In their comparison of 5 intrusion detection techniques for mobile cloud computing, they employ a set of metrics comprising methodologies, principle, performance, and limitations. Offered here is a high level framework for leveraging mobile cloud computing-based intrusion detection systems onto mobile applications. This framework consists of five components including mobile users, mobile apps, cloud-based applications, cloud-based intrusion detection systems, and heterogeneous 5G network.

Khan et al. (2013), examine security issues related to mobile cloud computing. They posit an architecture for mobile cloud computing which consists of four components including mobile client, mobile network, internet, and cloud service provider. Their survey compares: firstly, 8 existing lightweight security frameworks using a set of parameters; and secondly, 10 security applications for mobile cloud computing. The authors also discuss several research challenges regarding the following security and privacy issues in the context of mobile cloud computing: data and network security, data locality and integrity, web application security, data segregation and access, authentication and authorization, data confidentiality, and data breach. Similar issues were covered by (Paranjothi et al., 2017) who investigated mobile cloud computing offloading, computing distribution, and privacy. They proposed an architecture for mobile cloud computing which consists four components; mobile devices, wireless core, WiFi AP, and Regional Data Centers (RDC). Moreover, the research compares current frameworks in mobile cloud computing such as CloneCloud, MAUI, and Odessa. Furthermore, the survey discusses mobile offloading applications in mobile cloud computing and some privacy approaches that can be used when offloading such as encryption (Cui et al., 2013). look at energy efficiency in mobile cloud computing devices. More specifically, the authors present an overview of the universal energy estimation model for mobile devices, and provide a summary of energy-efficient wireless transmission mechanisms. As well, the authors propose an architecture for mobile cloud computing which consists of three components including mobile user, mobile service network, and cloud service provider. Their suggested research directions for energy efficiency in mobile cloud computing include cellular power management, and WiFi power management. (Wang et al., 2014), in their comprehensive survey concentrate on energy efficiency in location-based applications that run on mobile cloud computing environments. The survey compares 8 standalone optimizations for location-based applications and 10 cloud-based standalone schemes using locating sensing technologies. The comparison is based on a set of criteria such as sensors, scheme, accuracy, and coverage (Miettinen and Nurminen, 2010). analyze the main factors that influence energy consumption in mobile cloud computing. In particular, the authors provide an analysis of the computing energy efficiency and communication energy efficiency using multiple mobile devices.

Barbera et al. (2013) present a feasibility study on both mobile computation offloading (i.e., where computation is done in the cloud) and mobile application data storage in the mobile cloud computing environment. They demonstrate that mobile cloud computing can help reduce financial costs and energy consumption when reasonable data synchronization intervals (i.e., situations when mobile data needs to be synchronized with the cloud) are being considered (Ma et al., 2012). in their analysis focus on the issue of locating sensing energy efficiency in the mobile cloud computing environment. In particular, the authors propose an architecture for mobile cloud computing which consists of six components: end users, wireless network interface, hardware layer, infrastructure layer, platform layer, and application layer. Moreover, the authors differentiate several methods for locating sensing energy efficiency based on different criteria such as the tracking target, sensors used, and scheme.

Other surveys on mobile cloud computing focus on specific aspects such as application execution, augmentation approaches (e.g., offloading applications), heterogeneity, and multimedia. For example, (Ahmed et al., 2015b), comprehensively survey the application execution of frameworks applicable to mobile cloud computing. Their proposed architecture for mobile cloud computing consists of three components, these being mobile users, base station, and cloud datacenter. In addition, the survey identifies and classifies seamless application execution enabling approaches. Furthermore, their advantages and disadvantages are specified. Ahmed et al. compare 14 application execution frameworks based on a set of criteria including: cloud usage overhead, mirror deployment, pre-execution delay, caching support, and parallel execution support. Furthermore, these authors document research challenges for mobile cloud computing application execution including user-transparent cloud discovery, unobtrusive application offloading, optimal live Virtual Machine (VM) migration, seamless computational resources handover, and agile security and privacy mechanism.

Another recent comprehensive survey is that by (Zhou and Buyya, 2018), who focus on mobile cloud computing augmentation frameworks. They present a taxonomy of mobile cloud computing augmentation techniques, and these authors identify the advantages and disadvantages for each type. Moreover, the survey compares 24 mobile cloud computing augmentation frameworks with a discussion of pertinent research challenges in mobile cloud computing augmentation, for example service heterogeneity, service context-awareness, Quality of Service (QoS) management, and reliability and security management. Mobile cloud computing augmentation approaches are also covered by (Abolfazli et al., 2012), who classify augmentation approaches into two categories, hardware and software. Hardware approaches focus on generating high-end resources while software approaches focus on soft techniques such as conserving local resources and reducing resource requirements. In addition, the authors present a comparison of 7 mobile cloud computing augmentation approaches.

Shiraz et al. (2013), investigate existing distributed application processing frameworks for smart mobile devices in the mobile cloud computing environment. In particular, the frameworks are compared based on a set of criteria including offloading scope, migration granularity, and execution monitoring. Moreover, their study proposes an architecture which has three components including smart mobile devices, wireless network technology, and computational cloud. Shiraz et al. compare: firstly, 8 local resource sharing-based application offloading frameworks; and secondly, 9 server-based application offloading frameworks. The research challenges for mobile cloud computing application processing in their study are many, and include scalability and availability of services and resources, distributed application deployment, seamless connectivity and consistent distributed platform, homogeneous and optimal distributed platform and security and privacy in cloud-based application processing.

Sanaei et al. (2014), explore heterogeneity issues in mobile cloud computing and they classify heterogeneity challenges in mobile cloud computing into two dimensions, namely vertical and horizontal. That is, the categorization is based on where the heterogeneity is found such as mobile devices, clouds, or wireless networks and how it accords the version of the operating system, type of cloud, or type of wireless network. The architecture for mobile cloud computing posited here consists of four components: mobile devices, mobile network, internet, and cloud services provided in different deployment models that are either public, private, or in a hybrid format. Furthermore, the survey discusses research challenges for mobile cloud computing heterogeneity that include architectural issues, context-awareness, live VM migration, mobile communication congestion, trust, security, and privacy.

Khan and Ahirwar (2011) present a brief overview concerning issues of mobile multimedia database systems and the opportunities that mobile cloud computing brings. The authors classify mobile multimedia database systems issues into two categories, availability and environment challenges. They do this because of the nature of mobile cloud computing where services are delivered via the Internet and involves different environments. In addition, the authors propose an architecture of mobile cloud computing which comprises three components, namely mobile devices, mobile network provider, and mobile cloud platform. The research challenges discussed in their paper with reference to mobile multimedia database in mobile cloud computing include the following: network availability and intermittency, transit-time delay,

Table 1
Comparison of mobile cloud computing research surveys.

MCC Surveys	Focus	Proposed Architecture	Contributions	Analysis Technique	Determined Issues
Chetan et al. 2010	Generic	NA	- Overview about how MCC works. - Discuss some issues and possible solutions related to MCC. - Present the advantages of MCC. - Provide research challenges in MCC.	Qualitative Synthesis	- Absence of standards - Access schemes - Security - Need for elastic mobile Applications
Dinh et al. 2011	Generic	The architecture consists of five components including mobile users, network operators, Internet service providers, application service providers, and data center owners.	- Survey of MCC definition, architecture, and applications. - Propose MCC architecture. - Discuss issues, existing solutions and approaches. - Provide future research directions of MCC.	Qualitative Synthesis	- Low bandwidth - Network access management - Quality of service - Pricing - Standard interface - Service convergence
Kovachev et al. 2011	Generic	NA	- Survey existing work in MCC. - Give a definition of MCC. - Present a comparison of 12 mobile application models that are compatible with MCC. - Provide research challenges in MCC.	Qualitative synthesis Benchmark comparison	- Programming abstraction - Cost model - Adaptation - Cloud integration - Trust, security and privacy
Cox 2011	Generic	NA	- Overview of MCC devices, trends, issues, and enabling technologies. - Provide research challenges in MCC based on the comparison. - Provide research challenges in MCC.	Qualitative synthesis	- Device resource Poverty - Latency - Bandwidth - Security
Bahl et al. 2012	Generic	The architecture consists of four components including mobile devices, wireless core, WiFi AP, and Regional Data Centers (RDC).	- Propose MCC architecture. - Present a comparison of different programming models for MCC.	Benchmark comparison	NA
Qi and Gani 2012	Generic	The architecture consists of four components including mobile devices, wireless access point and mobile tower, servers and VMs.	- Propose MCC architecture. - Present an overview of mobile computing and cloud computing. - Provide a comparison of 4 MCC architectures. - Provide research challenges in MCC.	Qualitative synthesis	- Data delivery - Task division - Better service provisioning
Fernando et al. 2013	Generic	The architecture consists of five components including privacy and security manager, context manager, resource handler, cost manger, and job handler.	- Propose MCC architecture. - Present a taxonomy of issues in MCC. - Present an overview of 8 cost models in mobile clouds. - Provide a comparison of connection protocols used in mobile clouds. - Provide research challenges in MCC.	Qualitative synthesis Benchmark comparison	- Operational - Presentation and usability - Service level - Privacy and security - Context awareness - Data management
Rahimi et al. 2014	Generic	NA	- Present a comparison of 16 different MCC systems. - Provide research challenges in MCC based on the comparison.	Qualitative synthesis Benchmark comparison	- Power and execution time efficiency - Communication bandwidth efficiency - Security and privacy
Stergiou and Psannis 2017	MCC and IoT for big data applications	NA	- Present the main features and trade - offs of IoT and MCC. - Discuss the contributions of IoT and MCC in big data applications. - Provide research challenges in MCC.	Qualitative synthesis	- Security - Connectivity - Performance - Latency - Privacy
Wang et al. 2015	Generic	NA	- Categorize MCC into four categories. - Provide research challenges in MCC.	Qualitative synthesis	- Code computation (offloading) - Task - oriented mobile services - Elasticity and scalability - Security - Cloud service pricing
	Generic				NA

(*continued on next page*)

Table 1 (*continued*)

MCC Surveys	Focus	Proposed Architecture	Contributions	Analysis Technique	Determined Issues
Abdo and Demerjian 2017		The architecture consists of four components including E-UTRAN, mobile operator's core network, internet, and cloud service provider's network.	- Propose MCC architecture. - Present a comparison of 4 MCC architectures against the nonquantifiable requirements. - Present a comparison of 14 MCC applications performance when deployed across different MCC architectures using quantifiable metrics.	Qualitative synthesis Quantitative analysis Benchmark comparison	
Alizadeh et al. 2016	Authentication in MCC	Propose 4 MCC architecture models including: i) Distant immobile cloud, ii) Proximate immobile computing, iii) Proximate mobile computing, and iv) Hybrid computing.	- Propose 4 MCC architecture models. - Present a taxonomy of authentication in MCC. - Present a comparison of MCC authentication methods. - Provide research challenges for authentication in MCC.	Qualitative synthesis Benchmark comparison	- Heterogeneous infrastructure - Seamless handover - Identity privacy - Resource scheduling
Gai et al. 2016	Intrusion detection techniques for MCC	The architecture consists of five components including mobile users, mobile apps, cloud -based applications, cloud -based intrusion detection systems, and heterogeneous 5G network.	- Propose high level framework of IDS for MCC - Present a comparison of 5 intrusion detection techniques for MCC.	Qualitative synthesis Benchmark comparison	NA
Khan et al. 2013	MCC security	The architecture consists of four components including mobile client, mobile network, internet, and cloud service provider.	- Propose MCC architecture. - Present a comparison of 8 security frameworks for MCC. - Present a comparison of 10 security applications for MCC. - Provide research challenges for MCC security.	Qualitative synthesis Benchmark comparison	- Data and network security - Data locality and integrity - Web application security - Data segregation and access - Authentication and authorization - Data confidentiality - Data breach
Paranjothi et al. 2017	Offloading, distribution and privacy in MCC	The architecture consists of four components including mobile devices, wireless core, WiFi AP, and Regional Data Centers (RDC).	- Propose MCC architecture. - Present a comparison of 5 different programming models for MCC.	Qualitative synthesis Benchmark comparison	NA
Cui et al. 2013	Energy efficient wireless transmission in MCC	The architecture consists of three components including mobile user, mobile service network, and cloud service provider.	- Propose MCC architecture. - Provide research challenges for MCC energy efficient.	Qualitative synthesis	- Cellular power management - WiFi power management
Wang et al. 2014	Energy efficiency on location based applications in MCC	NA	- Present a comparison of 8 standalone optimizations for location sensing in MCC. - Present a comparison of 10 Cloudbased standalone schemes using locating technologies.	Qualitative synthesis Benchmark comparison	NA
Miettinen and Nurminen 2010	Energy efficiency of mobile clients in MCC	NA	- Provide an analysis of the computing energy efficiency and communication energy efficiency using multiple mobile devices.	Benchmark comparison	NA
Barbera et al. 2013	Bandwidth and energy costs in MCC	NA	- Present a report on the costs of energy using different synchronization frequencies and communication overhead.	Experiment	NA
Ma et al. 2012	Energy efficiency on location based applications in MCC	The architecture consists of six components including end users, wireless network interface, hardware layer, infrastructure layer, platform layer, and application layer.	- Propose MCC architecture. - Present a comparison of 8 energyefficient locating sensing schemes.	Qualitative synthesis Benchmark comparison	NA
Ahmed et al. 2015	Application execution in MCC	The architecture consists of three components including mobile users, base station, and cloud datacenter.	- Propose MCC architecture. - Present a classification of seamless application execution enabling approaches and specify their advantages and disadvantages. - Present a comparison of 14 application execution framework. - Provide research challenges for MCC application execution.	Qualitative synthesis Benchmark comparison	- User - transparent cloud discovery - Unobtrusive application offloading - Optimal live VM migration - Seamless computational resources handoff - Agile security and privacy mechanism
Zhou and Buyya 2018	Augmentation techniques in MCC	NA		Qualitative synthesis Benchmark comparison	

(*continued on next page*)

Table 1 (*continued*)

MCC Surveys	Focus	Proposed Architecture	Contributions	Analysis Technique	Determined Issues
			- Presents a taxonomy of MCC augmentation techniques and identified the advantages and disadvantages for each type. - Present a comparison of 24 MCC augmentation frameworks. - Provide research challenges for MCC augmentation techniques.		- Service heterogeneity - Service contextawareness - Quality of Service management - Reliability and security management
Shiraz et al. 2013	Application processing frameworks in smart mobile devices for MCC	The architecture consists of three components including smart mobile devices, wireless network technology, and computational cloud.	- Propose MCC architecture. - Propose a taxonomy of Application Processing Frameworks for MCC. - Provide a comparison of 8 local resource sharing based application offloading frameworks. - Provide a comparison of 9 server based application offloading frameworks - Provide research challenges for MCC application processing.	Qualitative synthesis Benchmark comparison	- Scalability and availability of services and resources - Distributed application deployment - Seamless connectivity and consistent distributed platform - Homogenous and optimal distributed platform - Security and privacy in cloud based application processing
Abolfazli et al. 2012	Smartphone augmentation approaches in MCC	NA	- Presents a taxonomy of smartphone augmentation approaches. - Present a comparison of 7 MCC augmentation approaches.	Qualitative synthesis Benchmark comparison	NA
Sanaei et al. 2014	Heterogeneity in MCC	The architecture consists of four components including mobile devices, mobile network, internet, and cloud services provided in different deployment models such as public, private, and hybrid.	- Propose MCC architecture. - Provide a taxonomy of heterogeneity roots in MCC. - Provide research challenges for MCC heterogeneity.	Qualitative synthesis	- Architectural - Context - awareness - Live VM migration - Mobile communication congestion - Trust, security, and privacy
Khan and Ahirwar 2011	Mobile multimedia database in MCC	The architecture consists of three components including mobile devices, mobile network provider, and mobile cloud platform.	- Propose MCC architecture. - Provide an overview of mobile multimedia database in MCC. - Provide research challenges for mobile multimedia database in MCC.	Qualitative synthesis	- Network availability and intermittency - Transit - time delay - Performance - Scalability - Integrity - Availability

performance, scalability, integrity, and availability.

Table 1 summarizes recent research surveys on mobile cloud computing by highlighting their focus, explaining the components of the proposed architecture for mobile cloud computing (i.e., if the authors proposed an architecture), expressing their contributions, identifying the analysis technique used to determine research challenges for mobile cloud computing and present these challenges. We have compared 26 surveys published from 2010 to the present day that either generally focus on: (i) mobile cloud computing, or (ii) specific areas related to mobile cloud computing. These can include such topics as authentication, intrusion detection techniques, security, privacy, offloading, distribution, energy efficiency, application execution, augmentation techniques, application processing, heterogeneity, and mobile multimedia.

Based on the comparison, we can observe that most recent surveys used qualitative synthesis and benchmark comparison analysis techniques to determine research challenges for mobile cloud computing and related areas. Conversely, unlike recent research surveys on mobile cloud computing, our work provides a holistic view of the current status of mobile cloud computing, especially given that our survey compares 30 representative mobile cloud computing research architectures that have all been published in the last 7 years. To the best of our knowledge, our survey is the only one that uses quantitative analysis (i.e., where statistical information about mobile cloud computing architectures is used), qualitative synthesis, and benchmark comparison analysis techniques to determine the challenges existing in mobile cloud computing. It is these aspects of our paper that represent the main contribution of our work to the knowledge on this subject.

3. Background of mobile cloud computing

3.1. Mobile computing

Mobile computing depends on the ability to use computer resources through mobile devices. Moreover, mobile computing enables the execution of tasks that have been traditionally done by normal desktops. In general, mobile computing is supported by three basic concepts: hardware, software, and communication (Satyanarayanan, 2011; Dinh et al., 2011; Liu et al., 2010). Hardware constitutes devices (e.g., tablet PCs and smartphones) that can be utilized by users. Software includes applications designed and developed to execute taskes in a mobile environment and communication which includes networks and protocols that can support the communication aspects of mobile computers such as Wireless Local Area Networks (WLAN), Long-Term Evolution 4G LTE and satellite networks. The mobile computing environment supports the following. First, there is **mobility** which allows mobile nodes or fixed nodes to connect with other devices' nodes in the mobile computing environment through Mobile Support Station (MSS) (e.g., servers and access points). Second, **diversity of network access types** refers to mobile nodes which can communicate using various types of access networks, for example Long-Term Evolution 4G LTE or Wireless Wide Area Network (WWAN) each with different communication bandwidths and overhead between the mobile nodes and the MSS. Third, **frequent network disconnection** means mobile nodes are not able to keep the connection consistent because of limited mobile nodes' resources such as battery energy and communication bandwidth. Fourth, regarding the issue of **poor reliability and security**, mobile node signals suffer from interference and eavesdropping in mobile networks which make security increasingly more important in mobile computing.

3.2. Cloud computing

Cloud computing is a technological approach that aims to increase capacity and capabilities of Information Technology (IT) networks by centralizing how data is stored and processed (Mell and Grance, 2011). It allows consumers to access applications without first installing them and increases access to personal information over the Internet (Armbrust et al., 2010). Furthermore, cloud computing has led to reduced costs of building IT infrastructures, and in acquiring new resources. Cloud computing service computers benefit from the multi-tenant architecture by maintaining one application (Noor et al., 2013). Cloud services are defined by five essential characteristics which include:

- **On-demand self-service:** A cloud computing service user leverages computing capabilities such as virtual machine time for processing and storage tasks whenever necessary without seeking the attention of each cloud provider.
- **Broad network access:** Cloud computing service users can access datacenters resources online using devices such as workstations, laptops, smartphones, or tablets.
- **Resource pooling:** Multiple cloud computing service users share the cloud service provider's resources (i.e., cloud computing resources includes processing power, storage, network bandwidth, and memory) in a multi-tenancy manner, where each user can run and stop these resources as needed.
- **Rapid elasticity:** Resources are elastically supplied or released automatically or manually depending on the consumer's needs. From a consumer perspective, the cloud resources capabilities are often unlimited and can be used anytime.
- **Measured services:** Cloud service providers may charge consumers based on a pay as you go pricing model. The cloud computing service usage is monitored and reported in real-time which ensures transparency between the cloud service provider and cloud computing service users.

3.2.1. Cloud service models

Software as a Service (SaaS): This refers to a service provided by a cloud application supported on a cloud infrastructure. Consumers can interact with the application through a user interface like a Web browser installed on different client devices. Consumers do not need to manage or manipulate any underlying cloud infrastructure such as servers or operating systems. However, they may be given limited control over particular application configuration settings (Mell and Grance, 2011).

Platform as a Service (PaaS): PaaS is another type of service which is built on the cloud infrastructure and involves developers acquiring applications and platforms which include tools, libraries and programming languages supported by the cloud service provider. The developer is not required to manage the underlying infrastructure such as network, server, storage except managing the deployed applications and settings of the environment hosting them (Armbrust et al., 2010).

Infrastructure as a Service (IaaS): This provides the cloud computing service user access to processing, network, storage, and other basic computing resources. IaaS also allows users to develop and execute software as well as operating systems and applications. The cloud computing service user is not required to manage the cloud infrastructure but still has control over the operating systems, applications and other resources like storage and networks applications, foe example firewalls (Noor et al., 2013).

3.2.2. Deployment models

According to the NIST definition of cloud computing, cloud services can be deployed using four development models including: (i) Private cloud, (ii) Community cloud, (iii) Public cloud, and (iv) Hybrid cloud (Mell and Grance, 2011) as shown in Fig. 1.

Private cloud: In this deployment model, a particular organization owns a datacenter regardless if it is managed by a third party or by itself. This cloud is usually for exclusive use and may be located onsite or offsite.

Community cloud: In this deployment model, the datacenter is

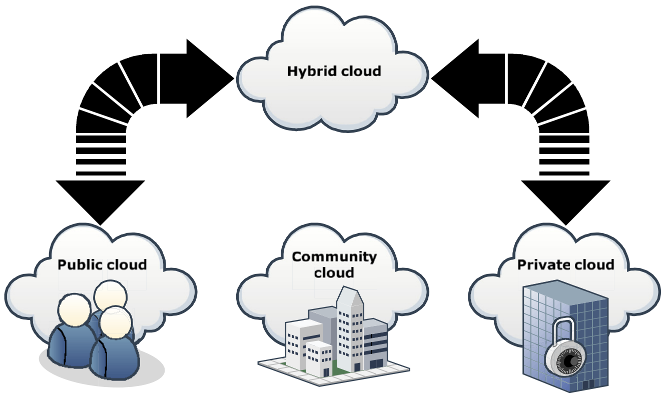


Fig. 1. Cloud services development models.

shared among one or more organizations in the community regardless if it is managed by a third party or one of the organizations owning it. This cloud is also for exclusive use and may be located onsite or offsite.

Public cloud: In this deployment model, the datacenter can be used by any cloud computing service user (e.g., a single user, research laboratory, company, or all of them together). This cloud is located at the same site as the cloud service provider.

Hybrid cloud: In this deployment model, two or more of the previously mentioned deployment models are used in a particular datacenter. This deployment model requires standards or patented technology which allows the portability of data and applications.

4. Mobile cloud computing architecture

Mobile phones are now ubiquitous in most people's daily activities and this has motivated companies to develop applications that can be easily accessed through mobile phones. The Internet, GPS and games applications are behind the worldwide popularity of mobile devices. However, limited resources (e.g., CPU, memory, and data storage) of mobile devices pose some design challenges to mobile application developers. To overcome these challenges, cloud computing is being used. Today's lifestyle often requires one to stay in touch through mobile communication technologies. Sending and receiving data are becoming easier to do. Mobile cloud computing combines the concepts of cloud computing and mobile computing (Dinh et al., 2011; Chetan et al., 2010). This new technology makes use of the capability of data storage and data processing by using cloud computing infrastructure through the Internet.

Fig. 2 depicts the architecture of mobile cloud computing which consists of three different layers: (i) *Mobile User Layer*; (ii) *Mobile Network Layer*; and iii) *Cloud Services Provider Layer*. These are discussed in more detail below.

- *Mobile User Layer*. This layer consists of many mobile cloud service users who access cloud services using their mobile devices (e.g., smartphones and tablets). These mobile devices connect to the *Mobile Network Layer* using Wireless Access Points (WAPs), Base Transceiver Station (BTS), or satellite.
- *Mobile Network Layer*. This layer consists of multiple mobile network operators which handle mobile users' requests and information is delivered through base stations. Mobile user requests and information transfers are handled by mobile network services such as Authentication, Authorization, and Accounting (AAA) which are provided by the Home Agent (HA). At this point, the mobile network operators help to identify the subscribers' data that is stored in their databases through their HA. After successful authentication and authorization, the operator delivers the mobile users' requests to a cloud through the Internet. The mobile user is then able to access the corresponding services as provided by the controllers in the cloud.
- *Cloud Services Provider Layer*. This layer consists of multiple cloud computing service providers which provide all types of cloud computing services including IaaS, PaaS, and SaaS. These cloud computing services are elastic and can be increased or reduced based on what cloud computing service users demand. Cloud computing provides services to users including those with mobiles can access cloud services via the Internet.

From a general perspective, we can say that this architecture demonstrates the effectiveness of cloud computing in meeting the mobile cloud computing service users' expectations. The main motivation behind the Mobile Cloud Computing (MCC) concept is complementing the mobile device's computing performance by employing a service oriented architecture such as the web, application and database servers. This concept must be supported through the creation of market oriented clouds. The architecture design for delivering web services must be able to deliver business oriented services, considering the consumers' needs such as ensuring the availability of the provided services, securing the communication channels, and preserving the privacy of their personal data. Several popular architectures have been used in MCC for different reasons such as augmented execution, data management, and energy efficiency. For instance, augmented execution is a technique which aims to increase the capability of mobile devices by overcoming the issue of resource limitations (e.g., computation, memory, and battery) by performing some computational tasks on the cloud using partitioning, migration, and scheduling techniques.

Early studies on augmented execution include CloudLet (Satyanarayanan et al., 2009), and CloudClone (Chun and Maniatis, 2009). It is well-known that one severe limitation of mobile devices is their limited resources. Various devices have been designed with cloud computing support in mind to execute various processing and storage tasks often through wireless communication technologies. For instance, Image Exchange, requires that a device be enabled to process and store large amounts of data. Through cloud computing, individuals are able to upload photos to the cloud immediately after capturing them where more energy can be saved. Facebook has taken advantage of this facility, and it became popular very quickly for this reason. MCC also simplifies data management by enabling the synchronization of several files and folders.

4.1. Dimensions for evaluating mobile cloud computing architectures

We use several dimensions to study issues related to mobile cloud computing, and identify the specific dimensions below by considering connectivity, energy sufficiency, and dynamics (i.e., mobile devices are connected and disconnected to cloud services around the clock). The distributed nature of mobile cloud computing is also taken into account.

- *Focus*: Mobile cloud computing approaches focus on several layers of the mobile cloud computing architecture. These layers include mobile user layer, mobile network layer, or cloud services provider layer. Therefore, it is crucial to determine what the proposed mobile cloud computing approach sets out to achieve.
- *Domain*: Given the complex structure of mobile cloud computing, which involves multiple interactions between mobile users and cloud service providers, some researchers propose mobile cloud computing architectures that support the cloud service provider. Others mean while support the mobile users. Therefore, it is crucial to determine the domain that the proposed architecture supports (i.e., service provider, service consumer, or both of them). The more domains the mobile cloud computing architecture supports, the more comprehensive it becomes.
- *Cloud Model Support*: Cloud-based mobile applications may depend on a particular cloud model (i.e., IaaS, PaaS, or SaaS) or multiple models. It is important to differentiate the type of cloud service

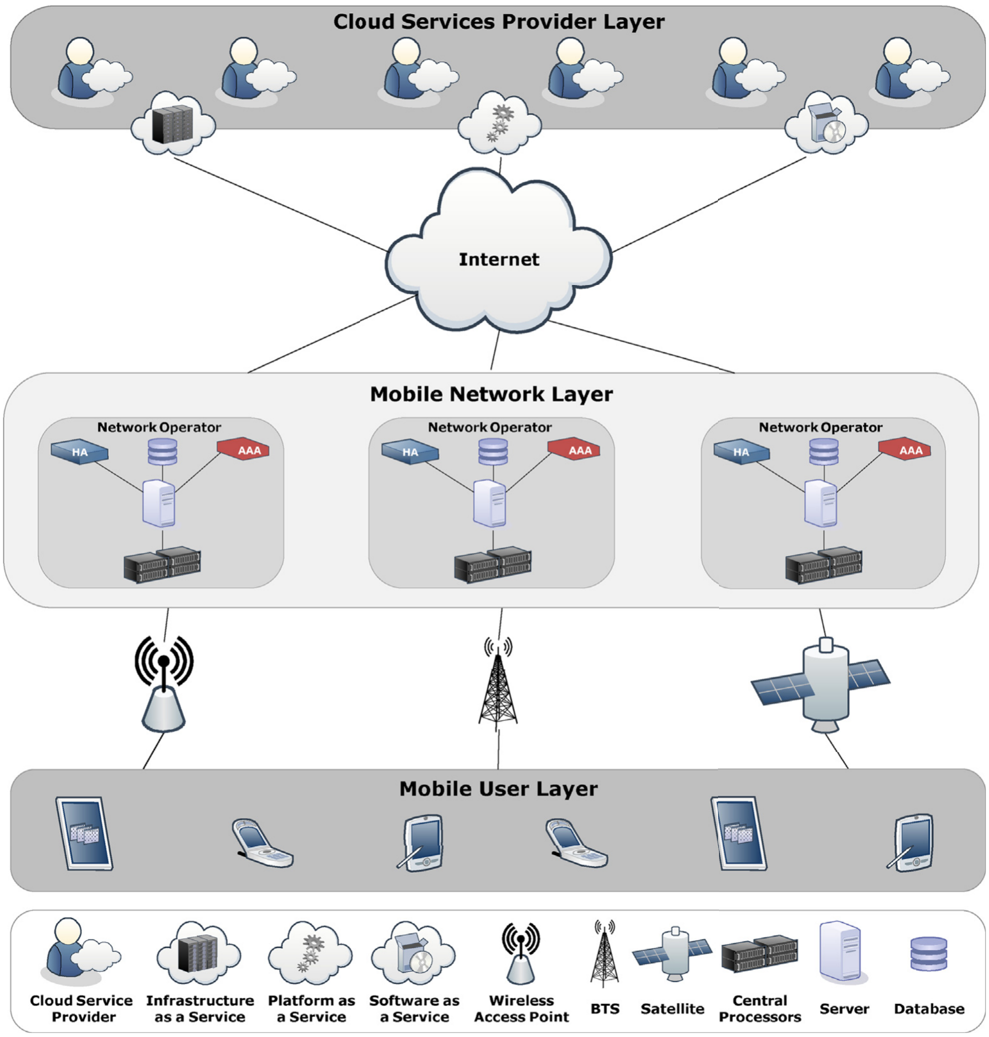


Fig. 2. Architecture of mobile cloud computing.

model that the proposed mobile cloud computing architecture supports. The more cloud services' models the proposed architecture can support, the more likely it can be adopted by industry.

- *Issue*: The nature of mobile cloud computing involves limited connectivity, energy constraint, the dynamic and distributed processing issues. Several researchers have proposed mobile cloud computing architectures to solve certain issues such as security and privacy, bandwidth and data transfer, data management and synchronization, energy efficiency, and heterogeneity. It is therefore important to identify what kind of problems the proposed mobile computing architecture is addressing.
- *Technique*: Depending on the issue that researchers are trying to address, the proposed mobile cloud computing architecture can exploit several techniques. Thus, it is crucial to differentiate the techniques used by researchers to address the specific issue under investigation. Such techniques can help other researchers to solve other problems relevant mobile cloud computing.
- *Architecture Design*: The mobile cloud computing environment is distributed and dynamic. Therefore, it is crucial that any proposed mobile cloud computing architecture should be scalable. Scalability means that the mobile cloud computing architecture has the ability to grow and shrink by increasing or decreasing the resources (and users) respectively. Mobile cloud computing architectures that follow a centralized architecture design will suffer from a number of issues such as scalability and security.
- *Application*: Many mobile applications exploit the benefits of mobile cloud computing including: (i) **Mobile Commerce** where goods and services are bought and sold through mobile devices exploiting cloud computing resources; (ii) **Mobile Learning (m-learning)** where mobile applications are designed based on e-learning standards and helps to avoid traditional m-learning limitations using mobile cloud computing capabilities (e.g., storage and computing); (iii) **Mobile Healthcare** mobile cloud computing can complement mobile medical applications by overcoming certain hardware limitations such as storage and energy consumption and other issues related to patients' information security and privacy; (iv) **Mobile Gaming** where mobile game applications (e.g., multi-player online games) require high resolution graphics and images, screen mirroring, minimal delays, and high bandwidth to cope with players' demands; and (v) **Mobile Social Networking** where cloud-based applications help mobile users to overcome storage limitations when they store their shared photos and videos so that they can be accessed directly from the cloud.

5. Recently proposed mobile cloud computing research architectures

In this section, we present an overview of major research architectures on mobile cloud computing that have been proposed in the literature from 2010 until now. These representative mobile cloud computing research architectures are then compared using the dimensions we have identified in Section 4.

5.1. Overview of major mobile cloud computing research architectures

- *A Mobile-Cloud Collaborative Traffic Light Detector for Blind Navigation* (Angin et al., 2010; Angin and Bhargava, 2011). propose a context-aware navigation system for the blind and the visually impaired which requires computationally intensive image and video processing algorithms. Essentially, it is a hybrid system of special camera glasses connected to a mobile device through Bluetooth technology. It works by transferring the captured images to a cloud platform to speed up the matching and recognition processing time and obtaining accurate results. In this way blind people can rely on using GPS signals and Wi-Fi based location tracking and Text to Speech (TTS) capabilities. The research focuses on the mobile user layer of the mobile cloud computing architecture supporting SaaS and IaaS cloud service models. The proposed approach has a strong emphasis on the service consumer domain with a decentralized architecture.
- *A Virtual Cloud Computing Provider for Mobile Devices* (Huerta-Canepa and Lee, 2010). propose a framework for creating virtual mobile cloud computing providers to address the issue of accessibility to cloud computing resources which is not always available and sometimes expensive. In particular, the proposed framework uses mobile devices as a virtual cloud computing provider by detecting nearby mobile devices which are stable (i.e., nodes with less load). This allows load balancing without having to connect to an IaaS cloud service provider. The research focuses on the mobile user layer of the mobile cloud computing architecture supporting IaaS cloud service models. The proposed approach places a strong emphasis on the service consumer domain with a decentralized architecture.
- *CloneCloud: Elastic Execution between a Mobile Device and the Cloud* (Chun and Maniatis, 2009; Chun et al., 2011). present a novel architecture where mobile applications are augmented using cloud computing resources to enhance processing speed and optimize energy consumption. In particular, CloneCloud enables mobile applications to be off-loaded just in the right amount to the cloud by using application partitioning and migration techniques. These studies focus on the mobile user and cloud service provider layers of the mobile cloud computing architecture supporting SaaS and IaaS cloud service models. The proposed approach places a strong emphasis on both the service consumer and provider domain with a decentralized architecture.
- *Cloud Computing for Enhanced Mobile Health Applications* (Nkosi and Mekuria, 2010). develop a framework for executing complex multimedia and security algorithms on the cloud instead of mobile devices. The proposed framework depends on the cloud computing protocol management model which delivers mobile health services. Here the focus is on the mobile user and cloud service provider layers of the mobile cloud computing architecture supporting SaaS and IaaS cloud service models. This approach concentrates on both the service consumer and provider domains with a centralized architecture.
- *Cloud Computing Through Mobile-Learning* (Rao et al., 2010). present a cloud-based system for education to improve the quality of mobile applications that are designed based on e-learning standards. The main objective of the proposed system is to avoid traditional Mobile-Learning limitations and reduce costs by using mobile cloud computing capabilities, for instance storage and computing. In particular, the proposed system is based on two different models, namely, the **Cloud Model** and the **Client Model** to facilitate the m-learning procedure. Rao et al. in their study focus on the mobile user layer of the mobile cloud computing architecture supporting SaaS cloud service models. The proposed approach focuses on the service consumer with a centralized architecture.
- *Efficient and Secure Data Storage Operations for Mobile Cloud Computing* (Rao et al., 2010). propose a holistic security framework to secure data storage in public clouds. The framework protects the privacy of the data during its retrieval from the cloud service providers. In particular, the proposed framework is based on a novel Privacy Preserving Cipher Policy Attribute-Based Encryption and an Attribute-Based Data Storage system as a cryptographic access control mechanism. The authors emphasize the mobile user and cloud service provider layers of the mobile cloud computing architecture supporting IaaS and SaaS cloud service models. The service consumer with a decentralized architecture is the focus here.
- *Energy-Efficient Incremental Integrity for Securing Storage in Mobile Cloud Computing* (Itani et al., 2010). propose a novel protocol for Mobile Cloud Computing (MCC) which maintains the integrity of storage services and optimizes energy consumption. In particular, the proposed protocol depends on incremental cryptography and trusted computing to protect the consumer data. The research focuses on the mobile user and cloud service provider layers of the MCC architecture supporting IaaS and SaaS cloud service models. This strategy puts a strong emphasis on the service consumer with a decentralized architecture.
- *Game Theoretic Modeling of Cooperation among Service Providers in Mobile Cloud Computing Environments* (Niyato et al., 2012). considered mobile applications such as online gaming that uses cloud resources that share a resource pool by multiple service providers to improve efficiency and utilization. To achieve these goals, they develop an admission control mechanism and a coalitional game model. The research emphasizes the cloud service provider layer of the mobile cloud computing architecture supporting IaaS cloud service models. The proposed approach focuses on the service provider with a decentralized architecture.
- *Lightweight and Compromise Resilient Storage Outsourcing with Distributed Secure Accessibility in Mobile Cloud Computing* (Ren et al., 2011). propose a family of lightweight secure storage schemes for mobile cloud computing assuming the existence of a distrusted cloud service provider which allows access for multiple mobile users. The research concentrates on the mobile user layer of the mobile cloud computing architecture supporting IaaS cloud service models. The proposed approach places a strong emphasis on the service consumer with a decentralized architecture.
- *MobiCloud: Building Secure Cloud Framework for Mobile Computing and Communication* (Huang et al., 2010, 2011). propose a novel framework called MobiCloud for ensuring the security of computation services in mobile cloud computing. Specifically, the proposed framework supports Mobile Ad-Hoc NETwork (MANET) functions such as information dissemination, routing, localization, and trust management. Paramount here are the mobile user and cloud service provider layers of the mobile cloud computing architecture supporting IaaS and SaaS cloud service models. The proposed approach focuses on the service consumer with a decentralized architecture.

5.2. Evaluation of mobile cloud computing research architectures

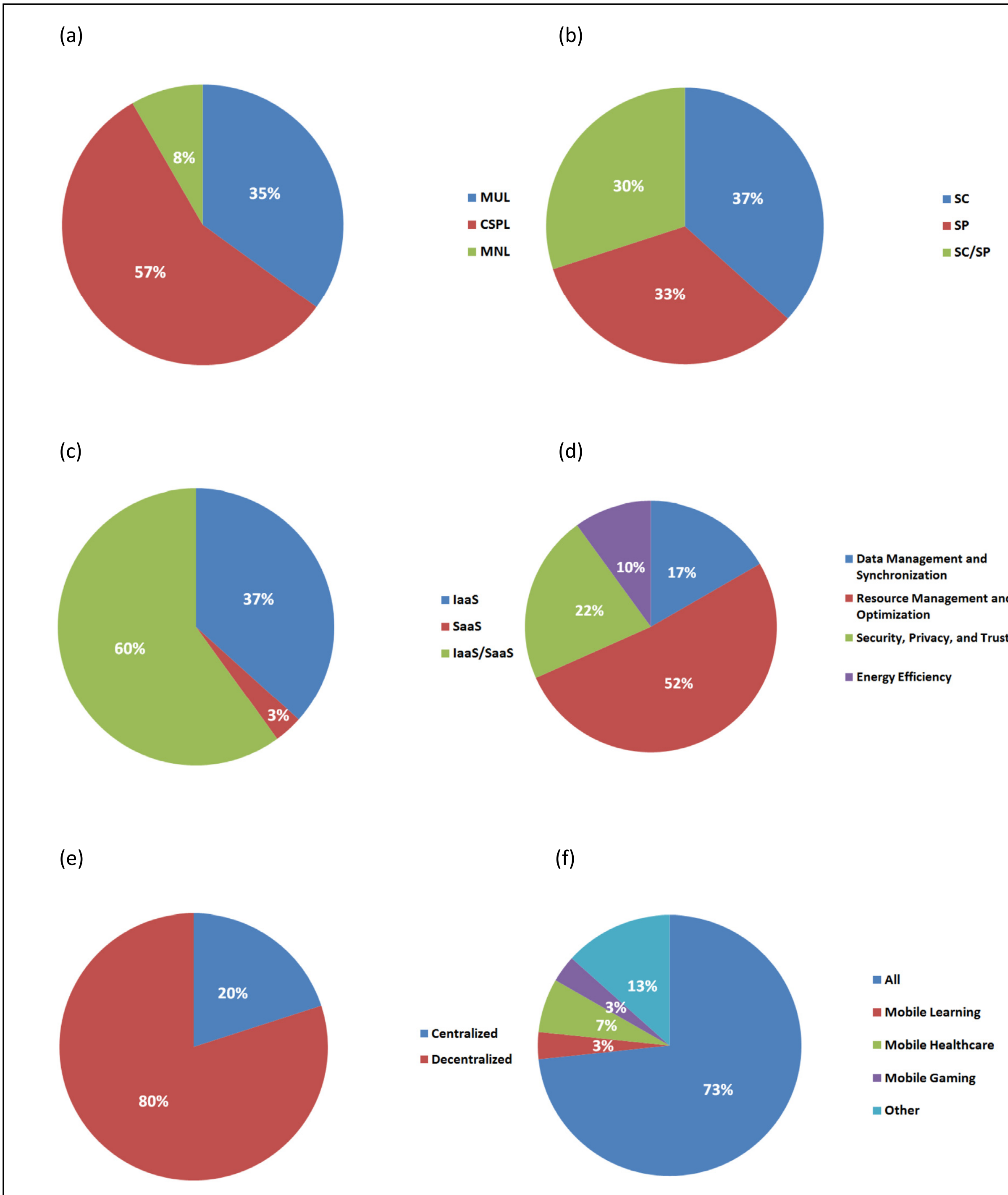
The evaluation of Mobile Cloud Computing (MCC) research architectures covers 30 representative research architectures which have all been published since 2010. Many mobile cloud computing research architectures addressed the issue of resource management and optimization (Zhou et al., 2015; Chen et al., 2015; Jo et al., 2015; Wan et al., 2014; Shiraz and Gani, 2014; Chen, 2015; Ahmed et al., 2015a; Liang et al., 2010; Hoang et al., 2012; Sanaei et al., 2012; Nguyen et al., 2012; Zhang et al., 2011; Kosta et al., 2011). Meanwhile, other studies examined issues such as data management and synchronization (Doukas et al., 2010; Choi et al., 2013), and energy efficiency (Barbarossa et al., 2014; Shiraz and Gani, 2014; Choi et al., 2013; Shiraz et al., 2015; Gai et al., 2016b), as well as, security, privacy, and trust (Liang et al., 2011; Jia et al., 2011). Fig. 3 illustrates our evaluation, based on the dimensions we have proposed in Section 4.

Fig. 4 (a) shows the results of mobile cloud computing research architectures based on the dimensions we have identified. Most of the

Architectures	Focus	Domain	Cloud Model Support	Issue	Technique	Architecture Design	Application
Angin and Bhargava 2011	MUL	SC	SaaS/IaaS	Data Management and Synchronization	GPS signals and Wi-Fi based location tracking - text to speech (TTS) capabilities	D	O
Gonzalo and Dongman 2011	MUL	SC	IaaS	Resource Management and Optimization	Using Mobile Devices as a virtual cloud computing provider	D	O
Chun, et al. 2011	MUL/CSPL	SC/SP	SaaS/IaaS	Data Management and Synchronization	Application partitioning and migration	D	All
Nkosi and Mekuria 2010	MUL/CSPL	SC/SP	SaaS/IaaS	Data Management and Synchronization - Security, Privacy, and Trust	Cloud Computing protocol management model	C	MH
Rao, et al. 2012	MUL	SC	SaaS	Data Management and Synchronization	Cloud Model Client Model	C	ML
Zhou and Huang 2012	MUL/CSPL	SC	SaaS/IaaS	Security, Privacy, and Trust	Privacy preserving cipher policy attribute-based encryption and data storage	D	All
Itani, et al. 2010	MUL/CSPL	SC	SaaS/IaaS	Security, Privacy, and Trust	Trusted crypto coprocessor	D	All
Niyato, et al. 2012	CSPL	SP	IaaS	Resource Management and Optimization	admission control mechanism and coalitional game model	D	MG
Ren , et al. 2011	MUL/CSPL	SC	IaaS	Security, Privacy, and Trust	A family of lightweight secure storage	D	All
Huang, et al. 2011	MUL/CSPL	SC	SaaS/IaaS	Security, Privacy, and Trust	MANET functions of information dissemination, routing, and localization	D	All
Doukas, et al. 2010	MUL/CSPL	SC	SaaS/IaaS	Data Management and Synchronization	Cloud Platform interface and cloud service client	C	MH
Choi, et al. 2013	MUL/CSPL	SC	SaaS/IaaS	Data Management and Synchronization - Energy Efficiency	Energy-efficient location-based service, Mobile cloud convergence, and connection	D	All
Liang, et al. 2010	MUL/CSPL	SC/SP	SaaS/IaaS	Resource Management and Optimization	Semi-Markov decision process	D	All
Hoang, et al. 2012	CSPL	SP	IaaS	Resource Management and Optimization	Semi-Markov decision process	C	All
Liang, et al. 2011	MUL/CSPL	SC/SP	SaaS/IaaS	Resource Management and Optimization - Security, Privacy, and Trust	Semi-Markov decision process	C	All
Sanaei, et al. 2012	MUL/CSPL	SC/SP	IaaS	Resource Management and Optimization	SOA	D	All
Jia, et al. 2011	MUL/CSPL	SC	SaaS/IaaS	Security, Privacy, and Trust	Secure data service mechanism	C	All
Nguyen, et al. 2012	CSPL	SP	IaaS	Resource Management and Optimization	Algorithms for dependent and Independent models	D	All
Zhang, et al. 2011	MUL/CSPL	SC/SP	IaaS	Resource Management and Optimization	Cost model and optimizing execution configuration	D	All
Kosta, et al. 2011	MUL/CSPL	SC/SP	IaaS	Resource Management and Optimization	Smart-phone virtualization in the cloud and level computation offloading	D	All
Wan, et al. 2014	MUL/CSPL	SC/SP	SaaS/IaaS	Resource Management and Optimization-Security, Privacy, and Trust	Architecture for integrating vehicular cyber-physical systems and MCC	D	O
Shiraz and Gani 2014	CSPL	SP	IaaS	Resource Management and Optimization - Energy Efficiency	Active Service Migration (ASM) framework	D	All
Chen 2015	CSPL	SP	IaaS	Resource Management and Optimization	A game theoretic approach for achieving efficient computation offloading	D	All
Ahmed, et al. 2015	CSPL	SP	IaaS	Resource Management and Optimization	Incorporate the network-centric parameters in the decision process of the application migration	D	All
Barbarossa, et al. 2014	MNL/CSPL	SP	SaaS/IaaS	Resource Management and Optimization - Energy Efficiency	Optimizing the communication and computation resources jointly with latency and energy constraints	D	All
Chen, et al. 2015	CSPL	SC	SaaS/IaaS	Resource Management and Optimization	Emotion-aware mobile cloud computing which offers personalized emotion-aware services and affective computing	D	O
Shiraz, et al. 2015	CSPL	SP	SaaS/IaaS	Resource Management and Optimization - Energy Efficiency	Energy Efficient Computational Offloading Framework (EECOF)	D	All
Jo, et al. 2015	MNL/CSPL	SP	SaaS/IaaS	Resource Management and Optimization	Device-to-device-based heterogeneous radio access network architecture	D	All
Gai, et al. 2016	MNL/CSPL	SC/SP	SaaS/IaaS	Energy Efficiency	Dynamic Energy-aware Cloudlet-based Mobile cloud computing (DECM) model	D	All
Zhou, et al. 2015	MNL/CSPL	SP	SaaS/IaaS	Resource Management and Optimization	Context-aware off-loading decision algorithm	D	All

Focus		Domain		Cloud Model Support		Architecture Design		Application	
MUL	Mobile Users Layer	SP	Service Provider	SaaS	Software as a Service	C	Centralized	ML	Mobile Learning
MNL	Mobile Network Layer	SC	Service Consumer	PaaS	Platform as a Service	D	Decentralized	MH	Mobile Healthcare
CSPL	Cloud Services Providers Layer			IaaS	Infrastructure as a Service			MG	Mobile Gaming
								O	Other

Fig. 3. Evaluation of mobile cloud computing research architectures.



Focus		Domain		Cloud Model Support	
MUL	Mobile Users Layer	SP	Service Provider	SaaS	Software as a Service
MNL	Mobile Network Layer	SC	Service Consumer	PaaS	Platform as a Service
CSPL	Cloud Services Providers Layer			IaaS	Infrastructure as a Service

Fig. 4. Mobile Cloud Computing Research Architectures Analysis. (a) Focus; (b) Domain; (c) Cloud model support; (d) Issue; (e) Architecture design; and (f) Application.

MCC research architectures (57%) examined the cloud services provider layer (CSPL). 35% of the proposed MCC research architectures investigate MUL only. Interestingly enough, however, we observe that only 8% of MCC research architectures have dealt with the Mobile Network Layer (MNL) which is still an important layer in the mobile cloud computing general architecture. Fig. 4 (b) depicts the results of MCC research architectures for the domain dimension. For this dimension, 37% of the representative MCC research architectures support the Service Consumer (SC). 33% of the proposed MCC research architectures support the Service Provider (SP) while the remaining 30% support both (i.e., SC and SP). Fig. 4 (c) summarizes the results of MCC research architectures for the cloud model support dimension. For this dimension, 37% of the representative MCC research architectures are applicable to the Infrastructure as a Service (IaaS) cloud model; 3% of the architectures are applicable to the Software as a Service (SaaS) cloud model; and more than half of the MCC research architectures are applicable to both IaaS and SaaS. However, surprisingly none of the MCC research architectures are applicable to the Platform as a Service (PaaS) cloud model.

Fig. 4 (d) depicts statistical information of MCC research architectures for the issue dimension. In this case, we note that there is a fair degree of variety in the MCC research architectures that we have reviewed. 52% of the representative MCC research architectures investigated the issue of resource management and optimization. 17% of the MCC research architectures have investigated data management and synchronization. 22% of the reviewed architectures have examined the security, privacy, and trust issues. Only 10% of the MCC research architectures have explored the energy efficiency issues. Fig. 4 (e) shows the results of MCC research architectures for the architecture design dimension. In this case, the majority of MCC research architectures (80%) have a decentralized design. Fig. 4 (f) depicts statistical information of MCC research architectures for the application dimension. In this case, we found that 3% of the representative MCC research architectures that we have reviewed, focused on Mobile Learning (ML) applications and a similar percentage of architectures work on Mobile Gaming (MG) applications. 7% of the representative MCC research architectures we reviewed, focused on Mobile Healthcare (MH) and the same percentage of architectures used other mobile applications. However, we observe that the majority of MCC proposed research architectures (73%) are generic and can be applied to all mobile applications.

6. Mobile cloud computing challenges and future research directions

For mobile cloud computing environments, we need efficient techniques to: first, satisfy the needs of mobile cloud service providers; and second, enable mobile users to fully utilize mobile cloud computing benefits so that longer battery life and increased storage, scalability, and reliability can be realized. Unfortunately, several issues concerning the mobile cloud computing environments still need to be addressed due to the connection limitation, energy sufficiency, dynamics, and distributed nature of mobile cloud computing environments. In particular, we identify the following research challenges, namely security, privacy and trust, bandwidth and data transfer, data management and synchronization, energy efficiency, and heterogeneity. Table 2 summarizes the mobile cloud computing research challenges, existing solutions and future research directions based on the evaluation of mobile cloud computing research architectures described in Section 5.

- *Security, privacy, and trust.* Security and privacy are crucial for mobile cloud computing environments because these characteristics determine the level of trust mobile users have when they off-load some of their jobs on their mobile devices and store their personal data in the cloud environment (Fernando et al., 2013; Khan et al., 2013; Shiraz et al., 2013; Dinh et al., 2011; Chetan et al., 2010). However, due to the dynamic and distributed nature of mobile cloud computing environments, achieving such requirements is still a major challenge. For example, if the number of communication channels used by the mobile device to transmit data increases, the potential for security breaches increases as the data travels to the cloud service datacenter. In addition, privacy in mobile cloud computing is quite different from traditional cloud computing because it involves more sensitive data such as location information from the Global Positioning System (GPS) when various location-based services are used. According to the statistical information in Section 5, 78% of mobile cloud computing research architectures do not have any particular mechanism for ensuring security at the mobile device level, communication level, or cloud services level and they do not preserve the privacy of mobile users. Therefore, there is a strong need for robust, efficient, and scalable techniques to ensure security and preserve the privacy of mobile users. Doing so will help mobile users to trust mobile cloud computing environments.
- *Bandwidth and data transfer.* Mobile cloud computing promises several benefits such as longer battery life and storage for mobile devices which can be accomplished through centralized processing and storage at the cloud service's datacenter. This approach, however, may lead to more communication overhead because of the increased bandwidth consumption and data transfers (Barbera et al., 2013; Fernando et al., 2013). Unfortunately, the increased communication overhead can also lead to additional hidden costs for mobile users and can constitute a barrier between mobile cloud computing consumers and the mobile cloud computing service providers. As we pointed out in Section 5 not much attention has been paid to the issue of bandwidth and data transfer and that is reflected in results we obtained from the review of recently proposed MCC research architectures shown in Fig. 4 (a) and (d). In other words, for the focus dimension, only 8% of the representative MCC research architectures have looked at the Mobile Network Layer (MNL) of the mobile cloud computing generic architecture. Moreover, for the issue dimension, none of the representative MCC research architectures have attempted to address the issue of bandwidth and data transfers. Thus, we argue that novel approaches that support efficient bandwidth utilization are needed to allow mobile cloud computing consumers to fully embrace it cost-effectively.
- *Data management and synchronization.* Due to the hardware limitations of mobile devices, mobile cloud computing allows computation off-loading where some computation tasks are transferred to the cloud datacenter. This process requires a proper data management system. In addition, cloud datacenters can synchronize mobile devices' applications and data to allow data accessibility from different devices or restoring data after a lost event. However, there is clearly a trade-off between off-loading compute-intensive tasks and bandwidth utilization. In other words, the same trade-off takes place with frequent synchronization intervals. On the one hand, high computation off-loading means more tasks can be accomplished. Moreover, more frequent synchronization intervals result in restoring the most recent lost data. On the other hand, increased bandwidth utilization means fewer tasks can be supported and restoring outdated data. As a result, it is important to understand when to off-load compute-intensive tasks and how frequently synchronization intervals take place. In other words, the mobile cloud computing environment requires strong data management and flexible data synchronization techniques. According to the evaluation provided in Section 5, not much work has been done in the last 7 years in the areas of highly efficient data management and synchronization. In fact, only 17% of mobile cloud computing research architectures focused on the issue of data management and synchronization. More research should be undertaken in these areas of mobile cloud computing in the future.
- *Energy efficiency.* Energy efficiency is one of the significant issues in mobile computing and mobile cloud computing is supposed to solve this issue and complement the hardware limitation in mobile devices (Cui et al., 2013). Energy consumers in mobile devices include the CPU, screen, GPS, cell radio, Bluetooth, wireless network interface card and other sensors. According to (Warden, 2015) the component of Smartphones that consumes the most energy is CPU and the estimated consumption of energy is between 500 and 2000 mW. This means that if we offload compute-intensive tasks to the cloud datacenter we will improve energy efficiency for mobile devices. Conversely, according to (Judge, 2013), 4G and Wi-Fi wireless data networks consume more energy than the datacenters themselves. This means there are additional hidden costs for mobile

Table 2
Mobile cloud computing research challenges and future directions.

MCC Challenges	Existing Solutions	Future Research Directions
Security, privacy, and trust	- Privacy preserving cipher policy attribute - based encryption and data storage (Zhou and Huang, 2012). - Trusted crypto coprocessor (Itani et al., 2010). - A family of lightweight secure storage (Ren et al., 2011). - MANET functions of information dissemination, routing, and localization (Huang et al., 2011). - Secure data service mechanism (Jia et al., 2011).	- Security should be assured in different levels of MCC including access control level, communication level and datacenter level. - End to end authentication should be used to cover all layers of MCC architecture (i.e., mobile user layer, mobile network layer, and cloud service provider layer. - Preserving the mobile user identity involves personal, communication, and location information. - The use of trust models can help mobile users in choosing the suitable cloud service provider.
Bandwidth and data transfer	NA[a]	- Bandwidth optimization and proper off - loading scheduling can help mobile users to effectively share wireless network bandwidth. - Backup intervals determination.
Data management and synchronization	- GPS signals and Wi - Fi based location tracking - text to speech (TTS) capabilities (Angin and Bhargava 2011). - Application partitioning and migration (Chun et al. 2011). - Cloud Computing protocol management model (Nkosi and Mekuria 2010). - Cloud Model and Client Model (Rao et al. 2012). - Cloud Platform interface and cloud service client (Doukas et al. 2010). - Mobile cloud convergence and connection (Choi et al. 2013).	- Proper data migration frameworks. - Efficient execution partitioning models. - Determining synchronization intervals using data related metrics such as outdated data and mobile users' access frequency.
Energy efficiency	- Energy - efficient location - based service (Choi et al. 2013). - Active Service Migration (ASM) framework (Shiraz and Gani 2014). - Optimizing the communication and computation resources jointly with latency and energy constraints (Barbarossa et al. 2014). - Energy Efficient Computational Offloading Framework (EECOF) (Shiraz et al. 2015). - Dynamic Energy - aware Cloudlet - based Mobile cloud computing (DECM) model (Gai et al. 2016).	- Offloading scheduling base on energy consumption metrics. - Execution partitioning models based on energy consumption metrics. - Synchronization intervals based on energy consumption metrics. - Empirical validation of energy consumption in MCC.
Heterogeneity	NA[a]	- Heterogeneity should be approached in different levels of mobile cloud computing including mobile devices level, network level and cloud level. - Middleware or translators can be used to solve incompatibility issues. - A call for MCC standard.

[a] Some of the existing solutions have been assigned Not Applicable (NA), which means there are no solutions proposed for this specific challenge in the data sample (i.e., in the MCC architectures evaluation). However, this does not necessarily mean there is no existing solution in the literature.

users which can affect the adoption of mobile cloud computing in the future. Based on the review results presented in Section 5, only 10% of mobile cloud computing research architectures have attempted to address the issue of energy efficiency. Thus, there is a strong need for efficient techniques to enhance energy optimization, which will help mobile users reap all the benefits of mobile cloud computing (Zeadally et al., 2012).

- *Heterogeneity*. In mobile cloud computing, we have a wide range of hardware and software technologies, communication networks, platforms, data formats and so on that need to interact and collaborate with each other (i.e., heterogeneity in hardware, software, and networks) (Sanaei et al., 2014). Mobile users need to access different types of data across multiple platforms which may increase complexity, for instance, different mobile applications use varied data structures. Such an environment requires intelligent techniques (Bello and Zeadally, 2016) to allow multiple devices and platforms to collaborate with each other. For example, middleware can be used to solve incompatibility issues. However, as we observed in Section 5, not a lot of attention has been given to the issue of heterogeneity which is reflected in review results of MCC research architectures shown in Fig. 4 (c) and (d). For the cloud model support dimension, none of the representative MCC research architectures are applicable for the Platform as a Service (PaaS) cloud model. Referring to the issue dimension, none of the reviewed MCC research architectures addressed the issue of heterogeneity. Therefore, we need novel approaches that can effectively support heterogeneity so that multiple devices and platforms in the mobile cloud computing environment can collaborate.

7. Conclusion

Over the past few years, mobile cloud computing has become a very active research topic and has consequently attracted the attention of many researchers. Mobile cloud computing has emerged to overcome the hardware limitations of mobile devices. In this work, we have presented a comprehensive survey of recent (focusing on the last eight years) mobile cloud computing architectures. We compared traditional cloud computing with mobile cloud computing. Furthermore, we compared 26 recent surveys published from 2010 to the present day on mobile cloud computing. Highlighted here were their focus, components of the proposed architecture for mobile cloud computing, the contributions they make, the analysis technique used to determine research challenges for mobile cloud computing and describing these challenges. Moreover, we have proposed a generic architecture to assess 30 recent representative mobile cloud computing research architectures using a set of assessment criteria. In this work, we have presented a holistic view of the current status of mobile cloud computing through a quantitative analysis and benchmark comparison to determine the major research challenges facing mobile cloud computing. Based on the analysis, we identified several research challenges that need further investigation. These challenges include security, privacy and trust, bandwidth and data transfer, data management and synchronization, energy efficiency, and heterogeneity.

Acknowledgments

Quan Z. Sheng's research has been partially supported by Australian Research Council (ARC) Future Fellowship FT140101247 and Discovery Project Grant DP180102378. The authors would like to thank the anonymous reviewers for their valuable comments and suggestions which helped us to improve the quality, content, organization, and presentation of this paper.

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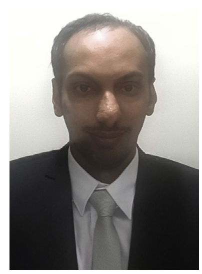

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