Journal of Universal Computer Science, vol. 21, no. 12 (2015), 1594-1634
submitted: 26/6/15, accepted: 27/11/15, appeared: 1/12/15 © *J.UCS*

Extending Mobile Cloud Platforms Using Opportunistic Networks: Survey, Classification and Open Issues

Shantanu Pal
(University of St Andrews, United Kingdom
sp66@st-andrews.ac.uk)

Abstract: With the tremendous growth of mobile devices, e.g, smartphones, tablets and PDAs in recent years, people are looking for more advanced platforms in order to use their computational applications (e.g., processing and storage) in a faster and more convenient way. In addition, mobile devices are capable of using cloud-based applications and the use of such technology is growing in popularity. However, one major concern is how to efficiently access these cloud-based applications when using a resource-constraint mobile device. Because it requires a continuous Internet connection which is difficult to obtain in challenged environments that lack an infrastructure for communication (e.g., in sparse or rural areas) or areas with infrastructure (e.g., urban or high density areas) with restricted/full of interference access networks and even areas with high costs of Internet roaming. In these situations the use of opportunistic networks may be extended to avail cloud-based applications to the user.

In this paper we explore the emergence of extending mobile cloud platforms using opportunistic networks. The motivation of this paper is twofold. First, we classify the available mobile cloud architectures according to their intent, the way they deliver services, and survey the state of the art research and issues related to their performance (e.g., battery power, storage capacity, bandwidth utilisation), environments (e.g., heterogeneity of networks, user's collaborations), robustness (e.g., scalability and availability of resources) and efficiency (e.g., context aware mobile services, access costs, energy consumption). Second, we devise a new 'mobile-opportunistic collaborative cloud' (MoCC) architecture which enhances mobile cloud platforms using opportunistic networks. Next, we outline the open issues and future research directions that need to be improved upon for delivering a more scalable, location-aware and context based service to the users.

Key Words: Mobile devices, Cloud-based applications, Opportunistic networks, Challenged environments
Category: C.2.0, C.2.1, H.4.3

1 Introduction

The use of the smart mobile devices (e.g., smartphones, tablets and PDAs) has grown significantly in recent years. These devices become more popular to its users due to the greater proximity/access of data according to the user's specific interests [Han et al., 2015]. In addition, the rise of cloud-based applications are significantly enhanced the computing resources (e.g., processing and storage) to the resource-constraint mobile devices using an available Internet connection [Li et al., 2009]. These cloud-based applications are fast replacing the traditional desktop and mobile applications (e.g., email, document sharing, multimedia communications, etc.) and the use of such applications by the users have become more convenient with these devices. *Mobile cloud computing* [Giurgiu et al., 2009] has thus arisen as a means for improving the capabilities of mobile devices with the abstraction of mobile technology and cloud-based services. There will be an estimated one trillion cloud-ready smart devices by the end of 2015[1].

The term 'cloud' [Mell and Grance., 2009] refers to a hosted service of a configurable distributed resource pool of networks, servers or storage over the Internet, where a user can gain an application (e.g., Google[2]) using a 'pay as you go' manner. In this paper, we use three terminologies for describing the tiers on cloud-based architectures, namely *edge clouds* [Bhardwaj et al., 2014], *cloudlets* [Satyanarayanan et al., 2009] and *infrastructure clouds* (that by default are designated simply as 'clouds') [Armbrust et al., 2010]. Edge clouds can be observed as the crowdsourcing of the smart mobile devices for providing computation, storage and connectivity. Cloudlets, on the other hand, can be considered to have a utility-like functionality. This provides reasonable latency sensitive computation, helps to improve the level of storage and act as a proxy to the Internet. The main objective of the cloudlet is to support resource-intensive and interactive mobile computing applications to the mobile devices in order to gain access to cloud-based applications with lower latency. Finally, the infrastructure clouds support the well-known highly available cluster based services.

Mobile cloud computing can be delivered when a mobile device use cloud-based services with the help of mobile apps installed inside the mobile devices and in other cases, when cloud-based applications are running inside the user's mobile devices. In former cases, this can be done in two ways; first, where applications are executed on a nearby infrastructure that acts as a virtual cloud (e.g., smartphones, tablets) [Marinelli., 2009] and second, applications are executed in the real cloud (e.g., Amazon Elastic Cloud Computing (EC2)[3] and Google App Engine[4]). In the latter case, cloud-based applications run inside the mobile devices utilising the resources (e.g., mobile platforms, memory or CPUs) in terms of 'cloudlets'.

However, from the device's point of view, major constraints of using these mobile devices are short battery power and limited memory size and from the network communication's point of view, the use of cloud-based applications in these devices need a constant Internet connection [Wang et al., 2015]. This is difficult to obtain in areas without a network infrastructure or areas with low network availability (e.g., in rural or sparse areas), but also in areas with infrastructure with restricted/full interference access networks (e.g., in urban and dense areas) as well as places where the cost of Internet roaming is simply too high (for

[1] https://www.ibm.com/developerworks/cloud/library/cl-mobilecloudcomputing/
[2] https://www.google.com/
[3] http://aws.amazon.com/ec2/
[4] https://appengine.google.com/

instance, in places where tourists try to avoid a high network access cost). In such situations the use of *opportunistic networks* [Conti and Kumar., 2010] may help to extend to access cloud-based applications instead of relying on a fixed infrastructure for communication or suppressed the network unavailability.

Opportunistic networks are one kind of mobile ad hoc networks (MANETs) that support the characteristics of Delay Tolerant Network (DTN) [Kevin., 2003]. But unlike MANETs, there is no end-to-end communication path available between the users for a message exchange. Connectivity opportunities in this type of networks are fully depends upon the users' interactions, mobility patterns and their willingness in message exchange. The user's mobility patterns are crucial in this kind of communication, since it helps to spread information in motion within the network and thereby improving the scope of message delivery. However, such mobility is considered challenging due to the sporadic contact of the users and their unpredictable behaviours [Karamshuk et al., 2011].

Nodes (users in a real-life) in such networks act as the receiver and sender to store, carry and forward messages to the next hop when they are on-the-fly. Unlike the traditional well established network communications, it does not assume the existence of an end-to-end routing path between the source and the destination nodes. Furthermore, it is possible that the destination node might not even be present within a network when the message is sent [Shikfa., 2010]. The message forwarding decisions are taken based on locally available information and contact opportunities between the users located in a fairly close distance, typically by using Bluetooth or Wi-Fi communication techniques [Qiu et al., 2015]. Depending upon these contact opportunities, messages are moved closer to their destinations and eventually they reach it. Nevertheless, these contact opportunities are infrequent in challenged environments.

Most of the recent research has been focused on the development model of the mobile cloud platforms and opportunistic networks [Huang et al., 2008] [Khan et al., 2013] [Mascitti et al., 2014], along with their issues and related challenges in their resources (e.g., battery power, storage) and communications (e.g., user's mobility, data privacy) [Fernando et al., 2013] [Nguyen et al., 2014] [Conti and Giordano., 2014] [Marin et al., 2015], but exactly how a mobile cloud platform can be extended using opportunistic networks in challenged environments is lacking in present research. We therefore envision future research on this issue and try to collate the present state of the art in this field. While this paper broadly surveys the emergence of extending mobile cloud platforms using opportunistic networks, the major contributions of this paper are as follows:

- We survey recent research advances and provide insights on the advantages and the limitations of different mobile cloud architectures. In addition, we classify the different mobile cloud architectures according to their mode of use.

- We provide a set of research challenges, with the intent to bring attention to motivate further research on enabling opportunistic networks in challenged environments through users' interactions and collaborations.
- We analyse the existing challenges and limitations for extending mobile cloud platforms using opportunistic networks. We then, devise a new 'mobile-opportunistic collaborative cloud' (MoCC) architecture that is capable of forwarding messages in challenged environments.
- We explore a set of unique applications where users take advantage of the locally available mobile cloud platforms with opportunistic networks, to overcome the limitations of both the device and its related communications within the network.
- We indicate open research questions and their possible countermeasures related to user's privacy and security, networks' heterogeneity, high mobility of the nodes, resource management and user's unpredictable behaviours.

The rest of the paper is organised as follows: Section 2 describes the motivation of the research. In Section 3, we discuss the classification of different mobile cloud architectures along with their challenges and limitations. We describe the emergence of the proposed 'MoCC' architecture, its components and potential application scenarios in Section 4. We discuss the open research issues, their potential countermeasures and the future research directions in Section 5, and conclude in Section 6.

2 Motivation

To understand the motivation of this research we discuss two use case scenarios. They are as follows:

(1) Bob is travelling to China. He is interested in photography. While Bob is visiting a rural place he finds that he has taken thousands of photos and his phone-memory is full, thus he is unable to take more photos. Bob really does not want to miss this wonderful opportunity to take photographs in this location and is searching for an Internet connection so that he is able to store/upload more photos to his cloud-assisted online photo sharing account (e.g., flicker[5]). This will allow his other friends to view his photos as well as allowing him to have more space in the memory of his mobile phone so he can take additional photos. But Bob finds that there is no Internet connection available in this location. So he may try to locate someone nearby who would allow him access to a cloud-assisted online platform to share his photos into the online account or allow him additional mobile storage so that he can store extra photos there temporarily.

[5] https://www.flickr.com/

In the above scenario, Alice may be able to help Bob but only after she is able to retrieve information about him and the type of service he is requesting so that their communication can be continued.

(2) Ron is visiting a museum in France and trying to find out the meaning of an ancient script that is written in a native form of French language. Ron is able to connect his mobile phone with the Internet where he may share this script with his online language based social community (e.g., cloudlingual[6]) but he does not choose to do so as for the limited bandwidth and high cost of Internet roaming. So he might think about someone nearby who is able to translate this native language into English which Ron can understand.

In such a situation, Ron may ask for help with this from the other visitors in the museum but there are some common challenges. Ron may not be able to find others who are able to translate or are even interested in the subject. Then there is the issue of how Ron will access the information and what incentives [Wang et al., 2012] [Scekic et al., 2013] can be offered to entice other users to help Ron with his query.

The above two scenarios indicate that there is a need of a platform for Bob, Ron and others who are interested in interacting with one another and are willing to share information at runtime. However, the challenge is, how can the information be advertised and retrieved by Bob and Ron? In both cases the users depend on the local user's mobile networks to obtain an available network connection to gain access to a cloud-assisted service/storage.

There are several service related issues (e.g., latency, bandwidth, costs, energy, shared wireless medium, etc.) that are concomitant to these types of communications. One of the concerns is how to locate the nearest user in a physical proximity [Orlinski and Filer., 2015]. In some public wireless networks, finding the physical proximity of a user is crucial as there are so many different network environments. A global centralised client-server mechanism may be adapted for this purpose but it is impractical to implement such a system in order to trace the user's movements and matching requests according to the their dynamic and unpredictable behaviours [Moreira and Mendes., 2015]. Also, single point of failure makes significant impacts to the whole system. Thus, the connection establishment between the global server and the client cannot be guaranteed.

To this end, there is a need to employ a decentralised network infrastructure. The most common existing decentralised mobile communications are the Peer-to-Peer (P2P) network communications technique [Chang et al., 2012]. Users store and manage information themselves with the help of their mobile devices and does not rely on a central component (e.g., a centralised server). This communication promises to share information among groups of peers and can create a collaborative information sharing environment in the absence of an Internet

[6] https://www.cloudlingual.com/

connection [Sapuppo., 2010]. However, the research is challenging in areas where a third party user (e.g., a tourist) is allowed the privilege of gaining access to such collaborative information sharing environments by joining/accessing locally available mobile networks.

On the other hand, Online Social Networks (OSNs) [Kumar et al., 2010] and Mobile Social Networks (MSNs) [Bulut and Szymanski., 2010] are fast becoming a more popular and integral part of our daily lives. The OSN is a Web-based communication platform for building social networking among its peers who share similar interests, activities and backgrounds in real-life connections. The MSN is also a networking platform where individuals connect with each other via their mobile devices to share common interests. Similar to OSNs, MSNs occur in virtual communities. Communication over OSN and MSN platforms using mobile devices have become an easy application for the users [Zhiwen et al., 2011].

Mobile users however, have been somewhat restricted in the virtual communities of OSNs and many are unaware of the social opportunities available to them [Jin et al., 2013]. Much research has been done to find out the nearby users and their possible communications in OSNs and MSNs, but most of them are tightly coupled solutions [Toninelli et al., 2011] [Girolami et al., 2015]. When the networks grow, more devices with different platforms as well as different application models join in the network, and thus creating a native mobile application for each of them is time consuming and inefficient. For example, a user using an application based on JXTA (Juxtapose)[7] is unable to communicate with the other users who are using a Universal Plug and Play (UPnP)[8] based application.

Therefore, there is a need to develop a platform independent, collaborative mobile cloud application which can adopt the heterogeneity of the networks, applications and devices in a challenged environment. To this end, we envision a more comprehensive and collaborative mobile cloud platform which can be enhanced by using opportunistic networks for a seamless access of cloud-based services with the help of locally available mobile networks.

3 Classification of Mobile Cloud Architectures

The combination of mobile technology and cloud-based applications deliver numerous successful adaptations of services (e.g., processing and storage), which tends toward a mobile cloud environment [Dinh et al., 2013]. In such environment, mobile devices and cloud-based applications become major parts of the network.

Ubiquity and mobility are two significant features in the mobile networks and the core technology of cloud-based application is a centralised distributed computing service [Qi and Gain., 2012]. Traditional infrastructure clouds are built

[7] https://jxta.kenai.com/
[8] http://www.upnp.org/

on clusters of servers. Data is placed in these clusters through layers of virtualisation and then high-level jobs are executed to process this data. In mobile cloud technology, edge clouds applications are used by one or more mobile devices where data originates and is processed in mobile devices. On the other way, mobile applications run inside the infrastructure clouds for offloading computations to the remote cloud servers [Pedersen and Fitzek., 2012].

Mobile data offloading can be done in two different ways, first, offloading in a static environment and second, offloading in a dynamic environment [Kemp et al., 2012]. In static offloading, the programmers pre-determine the application components and in dynamic offloading (also called context-aware offloading), the execution location of the components is not pre-determined. However, the traditional mobile application models do not support the development of applications that can execute only on mobile devices without computation offloading.

Khan et al. present a classification of mobile cloud architectures based on the offloading decisions and issues associated with the application models (e.g., performance, energy) [Khan et al., 2013]. Rahimi et al. present another classification of mobile cloud architectures based on the standard cloud-based service model that includes Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS) [Rahimi et al., 2014]. The IaaS provides storage, hardware and networking components e.g., servers. An example of IaaS is Amazon Simple Storage Service (Amazon S3)[9]. The PaaS provides user with an integrated environment for building, testing and deployment of custom applications. An example of PaaS is Microsoft Azure[10]. Whereas, the SaaS supports a software distribution with the specific requirements that happen remotely via an Internet connection. An example of SaaS is Salesforce[11]. Fernando et al. present a classification of mobile cloud architectures based on operational, end user and service levels issues, and also derive a basic level comparison of the different key issues in mobile cloud technology e.g., context-awareness, application related issues, data management and security, privacy and trust's point of view [Fernando et al., 2013]. Unlike the most of the techniques discussed in these classifications, we categorise different mobile cloud architectures into three specific class of architectures according to their mode of use, the intent they deliver services [Pal and Henderson., 2013]. They are mobile cloud *"Device to Cloud"* (D2C) architecture, mobile cloud *"Cloud to Device"* (C2D) architecture and mobile cloud *"Device to Device"* (D2D) architecture.

In the D2C class of architecture, mobile devices connect to the infrastructure clouds with the help of an Internet connection. In the C2D class of architecture,

[9] http://aws.amazon.com/s3/
[10] https://www.windowsazure.com/en-us/
[11] http://www.salesforce.com/uk/

cloud-based applications run inside the user's mobile devices may be in terms of cloudlets. Finally, in the D2D class of architecture, mobile devices create their own 'cloud environment' (can be viewed as a collaborative information sharing environment) with the help of the available mobile devices located in a physical proximity. A detailed discussion of these classifications is as follows:

3.1 Mobile Cloud "Device to Cloud" (D2C) Architecture

In this class of architecture, mobile devices connect to the infrastructure clouds with the help of an Internet connection (cf. Fig.1). Unlike the traditional cloud-based applications (e.g., via a desktop or server), the mode of using the devices are different in this case. As illustrated in Fig.1, users connect their mobile devices to the remote cloud servers with the help of mobile networks (e.g., wireless access points). According to the 'mobile cloud computing forum'[12], this type of mobile cloud is referred as an infrastructure where data storage and processing happens outside the mobile devices, which moves the computing power and storage away from mobile devices. In fact, mobile applications for data storage or processing move from mobile devices to a centralised distributed platform where a user can avail such services via a thin client or a Web browser through the Internet.

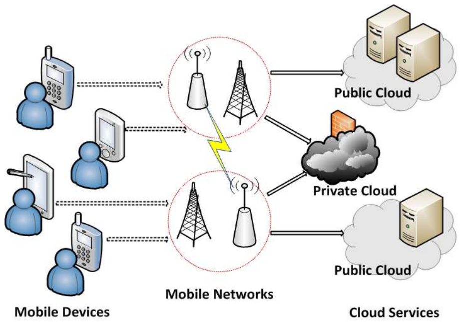

Figure 1: The D2C class of mobile cloud architecture is where users connect their mobile devices to the remote cloud servers through mobile networks for accessing cloud-based applications.

For instance, Li et al. propose a D2C class of mobile cloud architecture to deploy mobile computations to the remote cloud servers [Li et al., 2009]. In this, mobile agents help to deploy mobile computations to the cloud servers, executing

[12] http://www.mobilecloudcomputingforum.com/

the data processing outside the mobile devices. In addition, the mobile agents ensure a secure communication between the user's mobile devices and the cloud-based applications using a trust-based mechanism, which are controlled remotely by the users. However, a major concern is the available network bandwidth for a seamless data offloading between the mobile agents and the cloud servers.

Upon this, a lightweight mobile cloud offloading architecture called 'MoCa', which is able to provide dynamic offloading and enable customer resource managements of specific mobile traffic, can be employed [Banerjee et al., 2013]. This is a context-aware offloading architecture that does not require any additional network connectivity and performs equally well for a real-life traffic that requires a higher amount of network delays. An example of game server specific traffic offloading mechanism has been explored in this architecture (cf. Fig 2). The gaming service provider instantiates a virtual game-server engine inside a 'in-network' cloud-based platform. As illustrated in Fig 2, the in-network cloud-based platform is an instance of the infrastructure clouds that makes data transfer easier for the nearby mobile devices through dynamic data offloading. Mobile networks on the other hand, also create a software instance of a service provider gateway (S/P GW) in this cloud-based platform and keep it associated with the game server engine. Based on the requests from the mobile devices, the mobile networks send the signals for preparing the game's specific traffic and then divert this traffic to the game server engine. However, unlike the present motivation of our research, one major challenge is that, the MoCa requires a continuous Internet connection for offloading data and managing resources in game server engine.

Another D2C class of mobile cloud architecture, called 'volare', is presented in [Papakos et al., 2010]. This architecture, monitors the resources and context of the mobile device (e.g., hardware resources, environmental variables and user preferences), and dynamically adapts cloud-based services accordingly with the user's preferences at runtime. Thus, this architecture enables dynamic adaptations of the cloud-based resource management and binding information accordingly with the context of the mobile devices. Further, it provides a better service provision to the users with a cost benefit approach (by reducing unnecessarily high provision costs) and efficient bandwidth utilisation (by managing excess consumption of mobile resources) during the high network traffic. But unlike the scope of our present research, how to deploy this architecture in a 'collaborative' environment to gain benefit from these advantages in the absence of an Internet connection is missing.

Samimi et al. present a dynamic service-based D2C class of mobile cloud architecture, called 'mobile service clouds' [Samimi et al., 2006]. The goal of this architecture is to extend the infrastructure clouds service to the places with wireless Internet connections. This aims to provide efficient services at places

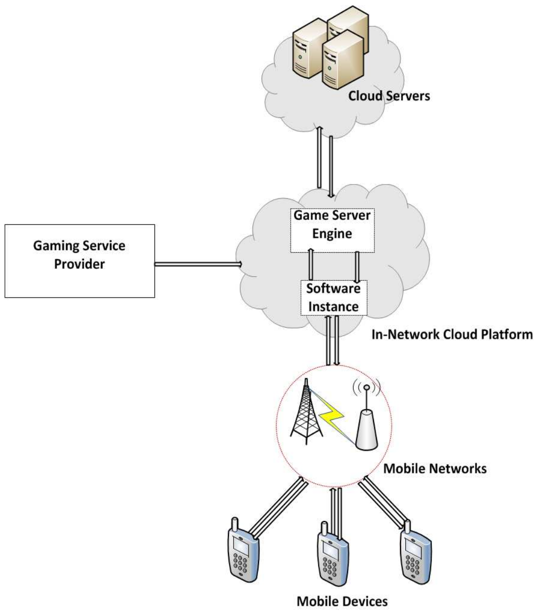

Figure 2: The 'MoCa', a D2C class of mobile cloud architecture is where users interact with the virtual game servers (referenced as In-Network Cloud Platform) through the cloud-based mobile networks.

that are away from the traditional wired infrastructures. This architecture helps for an automatic communication between the users within a network. Major components of this architecture are the service gateway, service coordinator and primary proxy. The service gateway is located at the entry point to the cloud servers. At first, the service gateway accepts the user's request and then designates a service coordinator (located inside the cloud server) based on the requested service. Then the service gateway chooses an appropriate primary proxy, located at wireless network edge, to send the results to the users. The service gateway also establishes a transient proxy for mobile devices to monitor the service path. Thus, the goal of the primary proxy is to maintain a service path between two end users. Unlike the 'MoCa' [Banerjee et al., 2013] and 'volare' [Papakos et al., 2010], this architecture explores the service provision during the time of disconnection through techniques such as Forward Error Correction (FEC) [Swierk and Baker., 1999]. In such techniques, router redirects the communication paths between the users, regardless of their network connectivity for direct communication, device or application. This explores user's collaborations for communications by maintaining a person-to-person reachability.

Klein et al. present a D2C class of mobile cloud architecture based on the concept of Intelligent Radio Network Access (IRNA) to provide an intelligent network access strategy to the mobile users [Klein et al., 2010]. The 'IRNA' seamlessly deals with the dynamics and heterogeneity of the available networks based on the user's application requirements.

This is a context management architecture which consists of three main components i.e., the context broker, context provider and context consumer. The context broker provides a Uniform Resource Identifier (URI) of the context provider through which the context consumer communicates directly with the context providers. The URI, is a string of characters that keep track the name of the resources and helps to identify the resources instantly. This reduces unnecessary delays by speed up the resource identification process in the network. Context broker maintains a registry cache for storing the context for the next use, thus it ensures an instant availability of the context information, which in consequence increase the speed of context data delivery. Context consumers can also directly connect to the service providers but data delivery speed increases with the use of the context broker's interactions.

Unlike the 'volare' [Papakos et al., 2010], the advantage of this architecture is that, the use of URI helps user for a faster interaction with the service providers in heterogeneous network environments. The quality of the contexts are controlled with the network availability, context accuracy as well as on the network delays. For instance, the smaller network delays increases the quality of context information.

Shen et al. present an intelligent cloud-assisted data access architecture named 'E-Recall' for personal multimedia information management, searching and sharing for mobile devices [Shen et al., 2010]. This is a D2C class of mobile cloud architecture which is based on the coordination between the mobile devices and cloud-based applications.

The main functional modules in this architecture are: query formulation, cloud-based indexing structure and user-centric media sharing and publishing. The query formulation module is responsible for optimising the user's information collected by different mobile devices. The cloud-based indexing structure module provides a database access method for data optimisation, and the last module helps to share and publish interactive digital multimedia resources (i.e., various formats of multimedia technological) to the mobile clients. Similar to the 'MoCa' [Banerjee et al., 2013], this architecture works seamlessly in dynamic heterogeneous networks. But unlike the 'volare' [Papakos et al., 2010], this framework requires a higher bandwidth of network utilisation for service delivery. Once again unlike the scope of our present research, devices in the 'E-Recall' architecture require a constant Internet connection for communication with one another.

Ou et al. present a D2C class of mobile cloud architecture that supports dynamic offloading mechanisms in a wireless mobile communication network (e.g., wireless ad-hoc Local Area Network) [Ou et al., 2007]. This architecture explores offloading mechanisms in 'failure/faults' circumstances. During failure/faults only the failed sub-tasks are re-offloaded, which improves the execution time without re-offloading the whole task once again. Compared with the Samimi et al. architecture [Samimi et al., 2006], major limitation of this architecture is that, it is based on wireless mobile communication networks which may suffers from connection problems in challenged environments (e.g., rural or sparse areas with limited connectivity) and any disconnections during the offloading execution treated a task/sub-task as a failure.

This architecture envisions similar goals with the scope of our present research by considering user's mobility in data forwarding. But unlike the motivation of our research, how to establish an alternative route using locally available mobile networks for a seamless communication between the users during a network disconnection is lacking.

Similar to the Ou et al. architecture [Ou et al., 2007], which consider user's mobility for data offloading, Li et al. present a D2C class of mobile cloud architecture with user's mobility-prediction based offloading method [Li et al., 2014]. In this, users in a physical proximity connect with one another for interactions. But during the connection failures, once again the complete task needs to be re-offloaded for further processing.

This architecture uses an adaptive probabilistic scheduler [Shi et al., 2014], which helps to schedule tasks from various source nodes to the nearby processing nodes. Further, based on the user's mobility patterns on different locations in varied time, this architecture uses two heuristic algorithms for data offloading. One is the Minimum Execution Time heuristic and the other is the Minimum Completion Time heuristic. In the former case, a scheduler offloads an application to the nearby node with the minimum execution time. In the latter case, a scheduler offloads an application to the nearby node with the earliest completion time. However, it is challenging to predict user's mobility patterns as this change with location and time [Karim and Mahmoud., 2013]. Unlike the Ou et al. architecture [Ou et al., 2007], during disconnections this architecture needs to re-offload the complete task instead of re-offloading the subtasks.

Chun and Maniatis present a D2C class of mobile cloud architecture for dynamic partitioning of a task and then offloading the partitions to the cloud servers [Chun and Maniatis., 2010]. The goal of this architecture is to save energy and ensure security of the sensitive data carried by the partitions. It structures the tasks and partitions them using a security algorithm to protect sensitive information within the task before offloading them to the cloud-servers. The proposed architecture is composed of three phases, they are: application structuring phase, partitioning phase and security phase. In the application structuring phase, cloud servers and clients have all of the parts of the applications which are executed between the client and the cloud servers. The partitioning phase contains a partitioning policy to minimise energy consumption. In the last phase, the proposed architecture executes a security algorithm locally (i.e., within the devices, before offload them to the cloud servers) to secure sensitive information. The sensitive information is marked based on the programmer's observation. This architecture improves the Ou et al. architecture [Ou et al., 2007] by using an efficient dynamic partitioning scheme between the client and the cloud servers. However, this architecture lacks accuracy as the partitioning process does not work in the absence of a network disconnection.

Kumar and Lu discuss a partition-based mobile data offloading architecture for the programming model to reduce energy consumption for the communication and computational side [Kumar and Lu., 2010]. In this D2C class of mobile cloud architecture, transmitted data and network bandwidth are major components to calculate the communication costs, whereas the computation cost is determined by the relative computation time. This architecture offloads data dynamically as the communication and computational components vary with the different circumstances. Unlike the Ou et al. architecture [Ou et al., 2007], in this architecture, data offloading improves the energy consumption for both the communication and computation. Similar to the Chun and Maniatis architecture [Chun and Maniatis., 2010], this architecture minimises energy consumption by using partition-based data offloading mechanisms.

Similar to the Kumar and Lu architecture [Kumar and Lu., 2010], Ravi et al. propose an energy management architecture for mobile devices [Ravi et al., 2008]. Based on the opportunity of the next charging point, this context-aware, energy management architecture warns the user when it detects a device's power limitation. The proposed architecture takes into consideration the current set of applications that are running in the device, the discharging rate and phone call logs to predict the unimportant calls and notify user accordingly.

An advantage of this architecture is that it tries to find the important applications (e.g., phone calls or sending texts) that should not be compromised by non-crucial ones (e.g., watching a video or listening to music). But the impact of the social interactions, present locations and various calling patterns for the different users in various times make it difficult to predict when the next important phone call needs to be answered. However, along with the similar line to our research, this architecture has more promise while travelling in rural areas or in a high cost of Internet roaming zone to determine the importance of an application. But unlike the scope of our research, this architecture requires a continuous Internet connection for communication which is difficult to gain in challenged environments.

In table 1, we summarise the various D2C class of mobile cloud architectures discussed in Section 3.1 , with their efficiencies. This includes context awareness, bandwidth utilisation, latency used, collaborations, cost efficiency and energy awareness.

Table 1: Comparisons between different attributes of mobile cloud architectures based on a D2C class of architecture. H=High, L=Low and M=Medium represents the efficiency of the networks. (CoAw: Context Awareness, BaUt: Bandwidth Utilisation, LaUs: Latency Used, CoBo: Collaborations, CoEf: Cost Efficiency and EnAw: Energy Awareness).

Architectures	***CoAw***	***BaUt***	***LaUs***	***CoBo***	***CoEf***	***EnAw***
[Li et al., 2009]	L	M	M	No	L	L
‘MoCa’ [Banerjee et al., 2013]	H	L	L	No	M	M
‘Volare’ [Papakos et al., 2010]	H	L	L	No	H	L
[Samimi et al., 2006]	M	L	M	No	L	L
‘INRA’ [Klein et al., 2010]	M	L	L	No	L	L
‘E-Recall’ [Shen et al., 2010]	H	H	H	M	L	L
[Ou et al., 2007]	L	H	H	L	L	L
[Li et al., 2014]	H	L	M	H	M	M
[Chun and Maniatis., 2010]	H	M	M	No	M	H
[Kumar and Lu., 2010]	H	L	L	No	M	H
[Ravi et al., 2008]	H	L	L	No	M	H

3.2 Mobile Cloud “Cloud to Device” (C2D) Architecture

In this class of architecture, cloud-based applications run inside the user’s mobile devices (cf. Fig. 3). The ‘Open Gardens’[13] defines the C2D class of mobile cloud architecture as *“the availability of cloud computing services in a mobile ecosystem. This incorporates many elements including consumer, enterprise, femtocells, transcoding, end to end security, home gateways and mobile broadband enabled service”*.

As illustrated in Fig. 3, cloud-based applications execute in ‘cloudlets’ that are located to the edge of mobile networks [Satyanarayanan et al., 2009]. Then the mobile devices access these cloud-based applications through these cloudlets. This can be done in two ways. First, by using a femtocell and second, by using a

[13] http://www.opengardensblog.futuretext.com/archives/2010/03/mobile/

Wi-Fi technology. A femtocell is used to improve cellular reception inside a building or home (i.e., an indoor network environment) [Chandrasekhar et al., 2008], whereas the Wi-Fi technology works better in an outdoor network environment [Qiu et al., 2015]. The aim of the C2D class of mobile cloud architecture is to use cloud-based mobile augmentation approaches. In which resourceful cloud-based applications leverage to enhance the computing capabilities (e.g., processing and storage) of the resource-constraint mobile devices [Abolfazli et al., 2014].

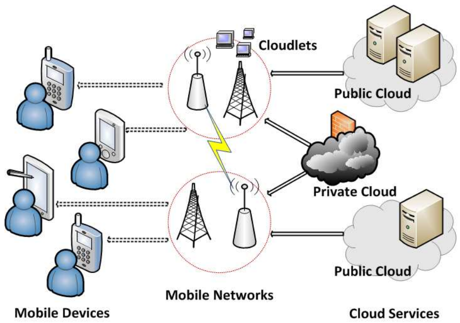

Figure 3: The C2D class of mobile cloud architecture is where resourceful cloud-based applications run inside the user's mobile devices with the help of the 'cloudlets'.

For instance, Huang et al. present a C2D class of mobile cloud architecture, named 'MobiCloud', which provides cloud-based applications to the local mobile nodes through a cloud-based mobile augmentation approach [Huang et al., 2010]. This architecture aims at focusing on the use of a systematic approach to understand the feasibility of integrating both the infrastructure clouds and MANETs communication technology.

The MobiCloud adopt cloud-based applications to create a virtualised environment for MANETs operation in multiple service provisioning domains according to the criticality of MANET's services and corresponding security requirements. In this architecture, each mobile node becomes a service node. A service node can be used as a service provider or a service broker according to its capability e.g., available computations and communication capabilities. Further, the MobiCloud supports a particular communication using maximum advantage of each mobile node in the system by utilizing cloud-based applications. Two major issues have been addressed in this architecture, they are: first, the lack of interoperability support in a heterogeneous MANETs communication that belongs to different administrative domains and second, issues related to locations, communication-privacy, reliability and survivability. However, this architecture is influenced by bandwidth and latency, which are major concerns for a seamless cloud-based mobile augmentation.

Another C2D class of mobile cloud architecture, named 'mCloud', is explored by Miluzzo et al., where mobile devices become a core component for executing cloud-based applications [Miluzzo et al., 2012]. The mCloud architecture is able to divide the cloud-based computations by slicing up a task into smaller subtasks to the other mobile devices according to the execution's requirements. This helps for a parallel data processing and alleviates the device's limitations (e.g., CPU, RAM, battery) for execution the whole task in a single device. This architecture not only addresses the technical perspectives of the C2D communications but also tries to find issues related to social domains by employing proper incentive mechanisms to the users to lend their devices for other user's computations. Similar to the goal of our present research, this architecture explores the user's interactions in social domain for communication. But unlike our motivation, this architecture does not mention how to collaborate seamlessly for information exchange in a social domain in a challenged environment.

Along with a similar view to the 'mCloud' architecture [Miluzzo et al., 2012], Shi et al. explore a C2D class of mobile cloud architecture where cloud-based applications run inside the mobile devices according to the execution's requirements and user's application requirements [Shi et al., 2014]. This improves the access speed and communication costs by using a resource allocation process and schedules offloading process with a mutual contention establishment with the cloud servers. This contention establishment improves in making offloading decisions in variable connectivity and enables an efficient resource management mechanism by using a task-allocation algorithm. But again, unlike our approach, this architecture requires a constant Internet connection for a communication establishment between the mobile devices and the cloud servers.

Verbelen et al. present a C2D class of mobile cloud architecture using the 'cloudlets' approach, where cloud-based applications have moved nearer to the user's mobile devices in the form of 'small data storage' [Verbelen et al., 2012]. This architecture is useful to employ areas, where Wide Area Network (WAN) communications make insufficient connectivity to access cloud-based services through mobile devices. The cloudlet infrastructure is 'mobile' where devices can join and leave the cloudlets at runtime. Cloudlets are used to mobile devices due to its widely-dispersed and decentralised Internet infrastructure and the ability to provide a high bandwidth of network utilisation. This in turn improves the communication's latency related issues.

Likewise the Verbelen et al. architecture [Verbelen et al., 2012], Koukoumidis et al. present a C2D class of mobile cloud architecture to improve data access, latency related issues and efficient energy management procedures for mobile devices [Koukoumidis et al., 2011]. The proposed architecture introduces a 'pocket cloudlet' concept, where full or a part of the cloud-based applications is stored inside the mobile device. The major benefit of 'pocket cloudlet' is that, it reduces the bottleneck of wireless communications and improves the latency as well as data access speed at runtime by increasing device's memory capacity. Unlike the Verbelen et al. architecture [Verbelen et al., 2012], the 'pocket cloudlet' is able to synchronise resources between edge clouds and mobile devices more easily and helps mobile device with efficient resource selection and their management. This architecture requires a memory to store the cloud-data, for instance, data can be stored in mobile cache.

In table 2, we summarise the various C2D class of mobile cloud architectures discussed in Section 3.2, with their efficiencies. This includes context awareness, bandwidth utilisation, latency used, collaborations, cost efficiency and energy awareness.

Table 2: Comparisons between different attributes of mobile cloud architectures based on a C2D class of architecture. H=High, L=Low and M=Medium represents the efficiency of the networks. (CoAw: Context Awareness, BaUt: Bandwidth Utilisation, LaUs: Latency Used, CoBo: Collaborations, CoEf: Cost Efficiency and EnAw: Energy Awareness).

Architectures	***CoAw***	***BaUt***	***LaUs***	***CoBo***	***CoEf***	***EnAw***
'MobiCloud' [Huang et al., 2010]	H	M	M	No	M	L
'mCloud' [Miluzzo et al., 2012]	M	M	M	No	M	L
[Shi et al., 2014]	H	M	M	L	M	M
'Cloudlets-based approach' [Verbelen et al., 2012]	H	L	L	M	L	H
'Pocket cloudlet' [Koukoumidis et al., 2011]	H	M	L	M	L	H

3.3 Mobile Cloud "Device to Device" (D2D) Architecture

In this class of mobile cloud architecture, mobile devices create their own 'cloud environment' with the help of the nearby mobile devices located in a fairly close distance (cf. Fig. 4). The term 'cloud environment' is referenced as an information sharing platform that helps sharing information available locally with one another located in vicinity. The key issue in such communication is the physical presence of the users carrying the mobile devices within the network [Karvounas et al., 2014].

As illustrated in Fig. 4, users communicate with each other within a network with the help of locally available mobile network communications. The D2D class of mobile cloud architecture enables direct communication between nearby mobile devices aims at improving information availability, overall throughput and device's energy efficiency [Alam et al., 2015].

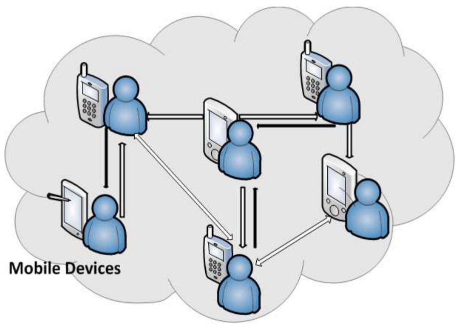

Figure 4: The D2D class of mobile cloud architecture is where users create their own 'cloud environment' by communicating with one another located in a physical proximity.

For instance, Mtibaa et al. present a D2D class of mobile cloud architecture which enables a scalable and autonomous Mobile Device Centric (MDC) approach based on the user's social network relations [Mtibaa et al., 2013]. The social network relations help to avoid unwanted communications by identifying foreign users (i.e., the users, they do not have a social relation to a user in the same network or in an outside network) during the content offloading between the devices. The MDC is autonomously grouped and its members are dynamically associated with each other for information exchange. In this architecture, devices become content producers, service providers and consumers at the same time. However, the user's privacy and security are major concerns while deploying a seamless service to the users. To this end, strong data encryption techniques can be employed [Meng et al., 2015] to secure communication between the users from the attackers/hackers who may steal/hack the user's sensitive information during data offloading. But unlike our approach, how to extend user's social relations further to access cloud-based applications during network disconnections is lacking in this architecture.

Pedersen and Fitzek present a D2D class of mobile cloud architecture that explores technical and social aspects [Pedersen and Fitzek., 2012] in such communication. In this architecture, mobile devices located in a physical proximity connect directly and create their own 'networks' for sharing information between each other. In technical aspect, there are issues related to P2P communications or overlay network techniques. On the other hand, social aspects deal with cooperation between the users by enforcing incentives in such cooperation [Wang et al., 2012] [Scekic et al., 2013]. However, the use of proper incentive mechanisms can mitigate a user's unpredictable behaviour but in a real-life application scenario it is more general and hard to avoid.

This architecture explores user's mobility during information exchange but offloading data to the cloud servers is difficult with the absence of an Internet connection. Thus, similar to our approach, this architecture deals with the user's mobility patterns for communication. But unlike the scope of our research, how to offload data to a cloud server in a challenged environment is lacking.

Similar to the Pedersen and Fitzek [Pedersen and Fitzek., 2012] architecture, Li et al. present a D2D class of mobile cloud architecture exploring the user's mobility patterns and social awareness in data forwarding [Li et al., 2014]. The goal of this architecture is to leverage social-aware D2D communication based on social relationships and human mobility on underlying cellular system. But once again, unlike our approach, this architecture does not indicate how to enhance these social relationships and human mobility for gaining access a cloud-based application in challenged environments.

Jin and Kwok present a D2D class of mobile cloud architecture for collaborative information sharing between users who have similar interests (for instance, playing the same audio/video files) [Jin and Kwok., 2010]. This architecture uses limited network bandwidth for searching and sharing information in places like a coffee shop, library or other small workplaces with the help of the nearby user's mobile networks. The motivation of this architecture is based primarily on the combined information received from multiple users located in a close physical proximity, where each user handle a part of the information e.g., images, sounds or text captions of a video file. Similar to our research, this architecture is promising to employ in places where mobile cloud platforms can be extended within a close range for collaborative information sharing among a group of users. However, how to enhance this architecture in places without a dedicated network infrastructure is lacking in this research. Moreover, this architecture does not consider a distribution policy to share large files between its peers.

Canepa et al. present a D2D class of mobile cloud architecture which helps user to dynamically locate an alternative route to communicate with the cloud servers during disconnection of a network service [Canepa et al., 2010]. This architecture explores the alternative route by locating users in a physical proximity who may have a stable network connection to offer. This connection establishment can be achieved by using the user's mobile networks.

In such way, a user is able to connect his/her mobile device with the cloud servers in an ad-hoc manner using other user's stable network connections. Similar to the Jin and Kwok architecture [Jin and Kwok., 2010], this architecture indicates how to get a route for communication via the nearby users who have a stable network connection. However, unlike the Pedersen and Fitzek architecture [Pedersen and Fitzek., 2012], this architecture does not consider user's mobility, device's processing capacity and user's privacy related issues when communicating with the nearby users.

Pal and Henderson present a D2D class of mobile cloud architecture where users (e.g., a tourist) can choose a service for sharing and storing their data, according to the available communication infrastructure and with the help of local user's mobile networks [Pal and Henderson., 2013]. The term 'local user' is referenced to the local people lives within a certain area. The proposed architecture, named 'MobOCloud', explores the use of opportunistic networking in a social collaboration platform for providing cloud-based applications to the tourists in areas that lack an Internet connection or places where the cost of Internet roaming is simply too high.

Local users store, carry and forward tourist's data to destinations on behalf of the tourists. This data forwarding process can be done without any direct interactions between the local users and tourists by keeping the data in a storage hub. Storage hubs are the static devices located in places where tourists and locals visit more frequently (e.g., tourist's attractions, museums, shopping centres). Tourists store their data in the storage hub and when a local user visits the place he/she collect that data and forward them to their intended destinations by allowing tourists to avail a cloud-based application. The fundamental of storing data at hubs is that, it improves battery power and memory capacity of the mobile devices.

Unlike the Canepa et al. architecture [Canepa et al., 2010], the data forwarding in the 'MobOCloud' architecture depends upon local user's mobility patterns and their social interactions. This communication, is however, influenced by several intermediate users who are willing to store, carry and forward data with the others within the network. Upon this, attractive incentive mechanisms can be employed to motivate more users in data forwarding [Li and Guo., 2015].

In table 3, we summarise the various D2D class of mobile cloud architectures discussed in Section 3.3, with their efficiencies. This includes context awareness, bandwidth utilisation, latency used, collaborations, cost efficiency and energy awareness.

Table 3: Comparisons between different attributes of mobile cloud architectures based on a D2D class of architecture. H=High, L=Low and M=Medium represents the efficiency of the networks. (CoAw: Context Awareness, BaUt: Bandwidth Utilisation, LaUs: Latency Used, CoBo: Collaborations, CoEf: Cost Efficiency and EnAw: Energy Awareness).

Architectures	***CoAw***	***BaUt***	***LaUs***	***CoBo***	***CoEf***	***EnAw***
[Mtibaa et al., 2013]	H	M	M	H	M	M
[Pedersen and Fitzek., 2012]	H	M	M	H	L	M
[Li et al., 2014]	H	L	L	H	L	M
[Jin and Kwok., 2010]	H	L	M	M	L	H
[Canepa et al., 2010]	M	L	L	H	M	M
'MobOCloud' [Pal and Henderson., 2013]	H	L	M	H	H	H

4 The Emergence of 'Mobile-Opportunistic Collaborative Cloud' (MoCC) Architecture

In this section, we devise a new *'Mobile-Opportunistic Collaborative Cloud'* architecture (MoCC) to extend mobile cloud platforms using opportunistic networks in challenged environments (cf. Fig. 5). Unlike the other traditional mobile cloud architectures, MoCC focuses on realising a loosely coupled, context-aware, service-oriented architecture that combines the D2C, C2D and D2D class of mobile cloud architectures (discussed in Section 3). In the D2C class of mobile cloud architecture, a mobile device offloads data to the cloud servers. In the C2D class of mobile cloud architecture, cloud-based applications run in mobile devices through mobile data augmentation. Finally, in the D2D class of mobile cloud architecture, devices communicate with one another using locally available network connections in a fairly close distance. The proposed architecture goes beyond these three classes of mobile cloud architectures and gains advantage from each of them. In this, both the D2C and C2D mobile cloud architectures are able to communicate with the D2D class of mobile cloud architecture and thus improves the data offloading/mobile data augmentation with the help of the locally available network connections. Returning to our motivation in Section 2, MoCC is promising for communication between the users and cloud-based applications instead of relying on a fixed infrastructure for communication or by avoiding a high infrastructural cost of communication (e.g., a high Internet roaming cost).

In general, the MoCC consists of two different technologies, which are then combines them into a single one. These are mobile cloud technology and opportunistic networking technology, by using local user's P2P communications

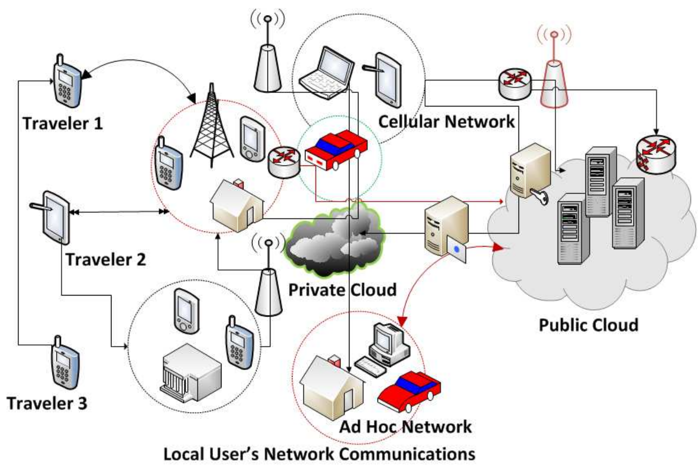

Figure 5: The emergence of 'Mobile-Opportunistic Collaborative Cloud' (MoCC) architecture is where travellers (e.g., tourists) can connect their mobile devices with mobile networks in proximity (referenced as Local User's Network Communications) for information storage and sharing. Travellers can communicate with each other but this depends upon the local user's mobile networks in order to gain access to a cloud-based application. Local user's P2P communications technology may be extended to provide such opportunities by allowing an Internet connection to the travellers.

technology. As illustrated in Fig. 5, travellers (e.g., tourists) can connect their mobile devices with the mobile networks available in proximity (cf. in Fig. 5 this is referenced as Local User's Network Communications). Local users (e.g., local people) play an important role in such communications for information sharing. Unlike the tourists, local users have direct access to the cloud-based applications and can forward/download data on behalf of the tourists.

Local user's network communications look into a specific class of application for mobile P2P networks in an opportunistic way. This network is formed by humans carrying mobile devices that communicate each other directly. In such communications, the physical presence of a user to support real-life collaborations among them is significant for storing, carrying and forwarding data from the source to destinations. The Bluetooth or IEEE 802.11b Wi-Fi wireless communications technologies are commonly used for this communication.

Next, we will explore the integration of mobile cloud technology and opportunistic networks and then discuss the MoCC architecture, followed by potential application scenarios.

4.1 The Integration of Mobile Cloud Technology and Opportunistic Networks

A major operation of mobile cloud technology is data offloading/mobile data augmentation via resource-constraint mobile devices. On the other hand, mobile opportunistic networks help to store, carry and forward data exploring user's physical interactions in a fairly close distance. Thus, while integrating mobile cloud technology with opportunistic networks, the data offloading/mobile data augmentation can be done with the help of the user's interactions exploiting their mobility patterns and social behaviours [Cheng et al., 2015].

In the offloading/mobile data augmentation part, resource constrained mobile devices discharge data to the cloud servers or cloud-based applications run in mobile devices [Kumar and Lu., 2010]. This helps to improve the device's battery power and increases computational performance. Traditional computational offloading/mobile data augmentation techniques are generally energy unaware and require improved bandwidth utilisation for communication. Therefore traditional computational offloading/mobile data augmentation mechanisms cannot be used directly in case of mobile cloud platforms in challenged environments because of the device's limited battery power and available bandwidth for communication [Chen et al., 2004]. Thus, present mobile devices require an application model that supports an efficient computation offloading method and being optimised for mobile cloud environments in terms of heterogeneity, context awareness, application partitioning overhead, network traffic, data cost, bandwidth and energy consumption in such challenged environments [Lei et al., 2013].

Collaboration among users is being facilitated with the advances in communication using opportunistic networks. With this network, users build an information exchange platform with the help of their social interactions and collaborations [Garcia et al., 2009]. Every node in opportunistic networks act as a receiver and sender to store, carry and forward messages. However, in a technological perspective, concern is, nodes do not have a unique address across different networks because of its high mobility. This makes it impractical to have an end-to-end communication path available between the nodes. In addition, in a social perspective, user's unpredictable behaviour is a common issue which can degrade the performance of the network through altruism [Hui et al., 2009]. For instance, users who do not wish to take an active participation in an opportunistic communication and thereby do not forward data packets. On the other hand, a selfish user, who takes an active participation but drops/delays packets that may have a high priority [Zhang et al., 2015]. We further discuss these issues with their possible countermeasures in Section 5.

User's mobility, interactions and cooperation, and routings for data forwarding are three significant issues when integrating mobile cloud technology with opportunistic networks [Conti and Kumar., 2010]. User's mobility is important as this exploit their interactions and cooperation between each other for sharing similar social interests. Routing strategies, on the other hand, play an important role for data forwarding between users by selecting the best possible path available.

In an opportunistic network, based on the user's behaviour, routing can be made in two ways [Moreira and Mendes., 2013] i.e., social-aware routing and social-oblivious routing. In social aware routing, a user has previous knowledge of the communication, while in social oblivious routing a user does not have any previous history of encounters. The most recent routing approaches are based on data replication over multiple paths. The typical routing algorithms are based on flooding, direct delivery, simple replication and history-based encounters.

In flooding (e.g., epidemic routing [Vahdat and Becker., 2000]), each node forwards the same copy of the message to another node when they meet, until the message reaches its destination. This may cause a high message delivery delay due to the nodes buffer size. In direct delivery (e.g., label routing [Hui and Crowcroft., 2007]), a node delivers a message until it comes to the direct contact with the destination node. In simple replication (e.g., spray and wait routing [Spyropoulos et al., 2005]), a source node generates multiple copies of the same message to a set of nodes called 'relay' nodes. The relay nodes are allowed to send copies of these messages only when they meet with the destination nodes and the message cannot be forwarded to another relay node in the network. In the history-based routing (e.g., prophet routing [Lindgren et al., 2004]), each node keeps track of the previous encounter history and forwards a message to the highest ranking node. Here the highest rank indicates the most numbers of encounters occurred between the nodes.

Back to the MoCC architecture, which extends mobile cloud platforms using opportunistic networks, are therefore promising to employ where a user can gain advantages of resource availability, efficient bandwidth, offloading computational applications via cloud-based applications and consequently improves communication's latency related issues. For instance, Hung et al. define a 'smart cities' [Hung et al., 2011] approach, where users can interact with each other with their mobile devices using opportunistic networks. This approach is useful for tourists to find a cloud-based application with the help of the nearby user's P2P communication networks. However, unlike the motivation of the MoCC architecture, this approach requires a continuous Internet connection to gain advantages for accessing a cloud-based application.

Our present research addresses this specific gap where we can use an opportunistic network to gain access to cloud-based applications in remote areas without infrastructure, but also in areas with infrastructure where the Internet access costs are simply too high. We therefore envision that, it is possible to extend mobile cloud platforms with the help of the opportunistic networks which are capable of providing cloud-based applications and dynamically manageable resources in a challenged environment.

4.2 The 'MoCC' Architecture

In this section we discuss the MoCC architecture. It consists of the following five basic components, they are: users, mobile devices, local users' mobile networks, Internet access points and cloud servers. The functional blocks of the envisioned architecture is presented in Fig. 6.

As illustrated in Fig. 6, the block, named user/mobile devices, is composed by the users (both the locals and tourists) and their mobile devices. The block local users' mobile networks helps user to communicate with one another in a physical proximity. Only the local user's mobile devices are able to connect themselves to cloud servers via an Internet access point, through which tourists can avail a cloud-based application. Between the blocks there is a need of service integration through which blocks can communicate with one another. The components of the MoCC architecture are discussed as follows:

4.2.1 User

Users (both the local users and tourists in this case) are defined as those who are using mobile devices and communicate with one another within a fairly close distance. Local users can connect their mobile devices to the cloud servers either via a fixed network service or via an Internet access point (e.g., Wi-Fi access points or hotspot) [Zhou et al., 2015]. Tourists try to send their requests for a specific cloud-based application to the cloud servers via local users' network communications.

While the benefits of cloud-based applications are the same, users may make their choices according to the service requirements based on the communication costs or device's energy requirements to run the application. Several issues (e.g., landforms, disaster, weather and buildings) can affect this type of communication and user's personal preferences are important in this case [Ali et al., 2015].

4.2.2 Mobile Devices

Mobile devices are referenced to the smart mobile devices carried by the users. These devices are connected to the mobile networks via telecom network providers (e.g., base transceiver station or satellite) or access points (e.g., Wi-Fi access points or hotspots) that establish and control the connections and functional interfaces between the networks and mobile devices (cf. Fig. 6). User's requests and corresponding information (e.g., ID and location) are transmitted to a central processor that is connected to servers providing mobile network services.

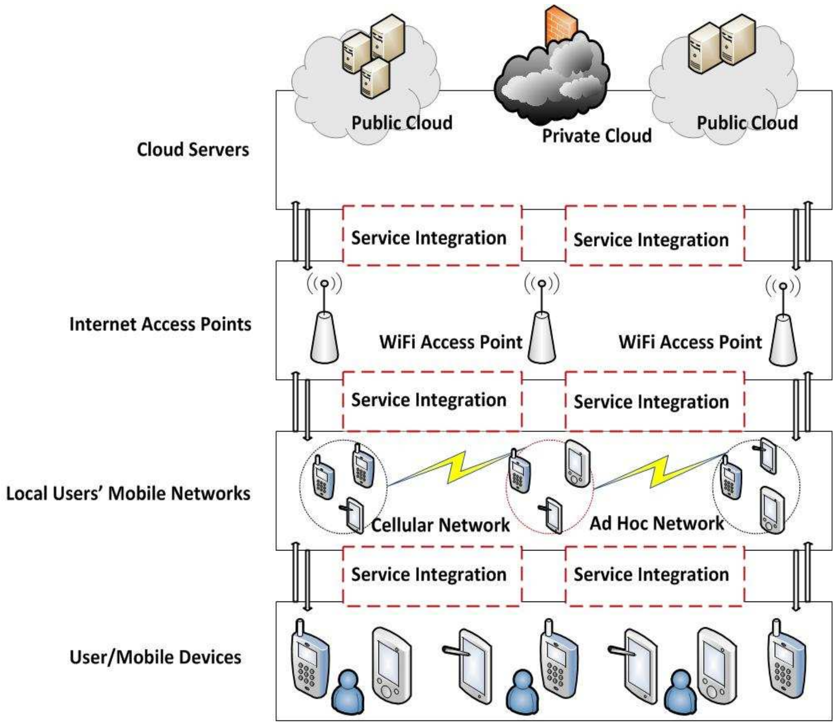

Figure 6: The functional blocks of the envisioned MoCC architecture. The block named user/mobile devices composed of users both the locals and tourists and their mobile devices. Users communicate with each other using local users' mobile networks. Only the local users can connect their mobile devices to the cloud servers via Internet access points for gaining access to cloud-based applications for the tourists. Between each block there is a need for service integration so that components in each block can communicate seamlessly with one another.

Mobile network operators provide services to mobile users as authentication, authorisation and accounting based on the user's data stored in their databases. Then, the user's requests are delivered to a cloud server through the Internet. In cloud servers, cloud controllers process the requests to provide mobile users with the corresponding cloud-based applications [Dinh et al., 2013].

Smart phones and tablets are the most popular choices to this end. Companies are steadily trying to build faster and more resource equipped mobile devices in terms of processor, memory and sensors. Statistics shows that: *"worldwide smart phone sales to end users reached 225 million units, up 46.5 percent from the second quarter of 2013. Sales of feature phones to end users totalled 210 mil-*

lion units and declined 21 percent year-over-year"[14]. Companies like Samsung, Nokia, Huawei, HTC, Sony and Apple are several of the leading companies at present producing smart phones [Chang et al., 2013]. For instance, Sony 'Xperia S'[15] comes with 1.5GHz dual core processor, 1GB RAM, 32GB data storage support and 1750mAh battery. Similarly, HTC 'One X'[16] has 1.5GHz quad-core processor, 1GB RAM, 32GB data storage support and 1800mAh battery. The most used mobile operating systems are Apple iOS, Research In Motion (RIM) Blackberry system (it offers java development environment), Android mobile operating systems, Windows mobile operating system, Nokia's symbian platform [Pejovic and Musolesi., 2015] [Xin., 2009].

4.2.3 Local Users' Mobile Networks

In MoCC, local users are an important part in the formation of the local users' mobile networks. This is basically a P2P communication networks where users connect with one another and share information available locally with their peers [Keshav., 2010]. When a node comes within the communication range of another node, then the opportunity to share information between each other is likely and eventually happens. User's mobility and their social interactions are important factors in this type of communication.

4.2.4 Internet Access Points

Internet access points are the places where users can connect their mobile devices with a Web-based application. These access points use either the traditional mobile network systems (e.g., mobile base station or satellite communication) or Wi-Fi, 3G and 4G mobile telecommunication technologies. The Wi-Fi based connections provide a higher bandwidth and lower delays as compared to a 3G connection which provides a lower bandwidth but a relatively higher delay [Lei et al., 2013]. On the other hand, 4G connections help users to improve with such issues as latency and bandwidth capacity. The 4G networks are capable of providing 100 Mbit/s (for Long Term Evolution (LTE) advanced standard) and 128 Mbit/s (for Wireless Metropolitan Area Networks (WirelessMAN) advanced standard) for mobile users, where 3G networks support a maximum of 14.4 Mbit/s [Dinh et al., 2013]. Moreover, Samsung introduces the 'Yes Buzz'[17] 4G cloud phone which has no Subscriber Identity Module (SIM) card and allows contacts to be saved synchronised on the Internet.

[14] http://www.gartner.com/newsroom/id/2573415/
[15] http://www.sonymobile.com/gb/products/phones/xperia-s/
[16] http://www.htc.com/uk/smartphones/htc-one/
[17] http://www.yes.my/v3/personal/devices/buzz.do/

4.2.5 Cloud Servers

Cloud servers are referenced to the virtualised cloud-based resources. Users connect their mobile devices with the cloud servers through Internet access points. While offloading mobile data to the cloud servers, it is important to select the proper cloud hosting environment for each service (e.g., shared hosting or dedicated hosting). Specifically, it must have offloading supports to enable user's applications at will [Slabeva and Wozniak., 2010].

4.3 Potential Applications

We will now discuss the potential applications of the proposed MoCC architecture. A few of them are as follows:

4.3.1 Searching for Users in Proximity

As discussed in motivation (in Section 2), Ron is travelling abroad and wants to know the meaning of an ancient script at a museum. Ron does not know this particular form of the foreign language. In this case, Ron may be interested in taking a photo of this script and share it with the nearby mobile users who may be interested to share the meaning of this language so that he can understand it.

In this situation, Ron can use a D2C class of mobile cloud architecture e.g., 'volare' [Papakos et al., 2010] (discussed in Section 3.1), but this would require a constant Internet connection for communication. Therefore, in such situations the MoCC architecture can be employed to find a nearby user who may be able to find the meaning of the script for Ron. This in consequence, reduces the communication's cost in terms of Internet roaming for searching the information over a cloud-based application. In addition, this removes the geographical barrier and can avoid the need of an active Internet connection. This is useful in areas that lack an infrastructure for communications, but also in areas with high costs of Internet roaming.

4.3.2 Crowdsourcing

Using mobile cloud technology, crowdsourcing [Fernando et al., 2012] is possible for information exchange. In this, mobile devices form an environment that could allow users the ability to find useful information within a shorter range. This can be achieved with the D2C class of mobile cloud architectures e.g., the 'E-Recall' [Shen et al., 2010] and the Ou et al. architecture [Ou et al., 2007] (discussed in Section 3.1), but again the concern is that the mobile devices need a continuous Internet connection to avail edge clouds resources [Ren et al., 2015].

Therefore, research is promising to use the MoCC architecture by exploring the locally available mobile networks, instead of relying on a fixed infrastructure for communication. An example would be, using his mobile device; Ron (in Section 2) may be able to locate some interesting people in the museum who can share the required information to understand the meaning of the ancient script which is written in a foreign language.

4.3.3 Sensor Data Applications

Smart phones are able to connect Global Positioning System (GPS) services for finding a specific location [Whipple et al., 2009]. It is also possible to calculate device's location and speed with a sufficient accuracy. This is useful when searching for specific locations e.g., travel destinations, maps or tourists attractions. This can be done by using the C2D class of mobile cloud architectures e.g., the 'MobiCloud' [Huang et al., 2010] and the 'mCloud' [Miluzzo et al., 2012] (discussed in Section 3.2). But unlike the MoCC architecture, these C2D architectures require a constant Internet connection that may be unavailable in rural or sparse areas that lack an infrastructure for providing an Internet connection, but also in urban areas with infrastructure with full/restricted interference access networks. Therefore, in such areas the use of the MoCC architecture is promising.

4.3.4 Smart Tourism and Travel

Smart tourism tries to solve the scheduling, planning and recommendations in the tourism industry [Gretzel et al., 2015]. This may be a travel schedule, ticket arrangements or the booking of a hotel which is helpful to the tourists who would be travelling. For instance, as outlined in Section 4.1, the architecture presented by Huag et al. for a smart travel system which consists of a real-time travel searches, personal demands and task service management services for the tourists [Hung et al., 2011]. But again, unlike the scope of our present research, this architecture requires a continuous Internet connection to get users connected with one another. In such situations the D2D class of mobile cloud architectures can be employed to avail information locally e.g., Pedersen and Fitzek architecture [Pedersen and Fitzek., 2012] and Jin and Kwok architecture [Jin and Kwok., 2010] (discussed in Section 3.3), but this is difficult to get information from a global community for which an Internet connection is unavoidable. Therefore, using the MoCC architecture, that combines local and global connectivity, research is promising when travelling in areas with no Internet connection or in areas with the high Internet access costs. This would explore avenues to allow the use of smart tourism applications with the help of the local users' mobile network communications to get a global connectivity.

5 Open Issues

We have discussed the state of the art research for extending mobile cloud platforms using opportunistic networks in challenged environments and explored their challenges and potential applications (in Section 4). However, there are several open research questions and issues which future research would need to address. In this section, we indicate some of those open research questions and issues related to user's privacy and security, heterogeneity of networks, node's mobility management, dynamic resource management and unpredictable user's behaviour. They are discussed as follows:

5.1 User's Privacy and Security

In opportunistic networks, communications solely depend upon the user's interactions and their willingness to store, carry and forwards messages for others. In some cases, users may not be interested in sharing information (e.g., their present location or name) with the other users. Users may be concerned about their own privacy and data confidentiality that could be leaked, stolen or even tampered with by others [Lilien et al., 2007]. Due to the absence of a centralised controlled system over the users in an opportunistic network, it is impractical to employ a fixed security solution in such communication [Conti et al., 2011]. We indicate the open research questions for future research are as follows:

- How can we preserve the privacy and confidentiality of user's data while keeping the same routing performance in the network?
- What are the metrics that need to be addressed for preserving the privacy and confidentiality, and how to monitor them while transferring data through opportunistic networks?
- How can a heterogeneous mobile cloud platform preserve user's relational privacy in sharing data among each others?

Upon this, a dynamic privacy-aware framework can be enforced [Wang., 2010], which can mitigate data leakage in such communications by using user's relation-privacy. In this, users keep a secure, dynamic and reliable data communication only between the trusted users (e.g., between close friends).

5.2 Heterogeneity of Networks

Nodes belong to a heterogeneous network relies on various communication technologies and protocols [Sanaei et al., 2014]. In opportunistic networks nodes do not depend upon a global infrastructure. This is due to the fact that, connections may vary from place to place (e.g., rural and urban areas). Therefore, nodes do not have a unique address across the different networks. This raise the requirements for an improved authentication and trust establishment mechanism in data forwarding. In relation to this, we indicate the open research questions for future research are as follows:

- How can we secure communications for a node travelling via different network addresses in a heterogeneous network?
- How to design a reputation-based framework guaranteeing the use of reliable relations in data forwarding in heterogeneous mobile cloud platforms?

To this end, a security mechanism that allows detecting dynamic changes of the computing environment according to the user's preferences can be employed [Zhang et al., 2009]. This enables resource-constraint mobile devices a unique security solution for authentication by identifying non-trusted users, and enforce a secure session management between user's mobile devices and cloud servers across heterogeneous mobile cloud platforms.

5.3 Node's Mobility Management

In opportunistic networks nodes are extremely mobile and disruptions in paths are frequent. It is thus impractical to establish a stable end-to-end route for communication between nodes during data transmission [Karamshuk et al., 2011]. To this end, we indicate the open research questions for future research are as follows:

- How can we keep the routing solutions highly dynamic and flexible, and not dependent on a predefined path?
- How can a third-party user efficiently detect a minimum path that connects a group of target users on a collaborative mobile cloud platform with the minimum number of Web accesses needed for online discovery (e.g., to find a cloud-based application)?
- How to build a framework which effectively spreads the congestion condition at high-centrality nodes to the entire network by social influence to notify data sources of the congestion situation so that the other nodes can adjust the data generation rate to relieve network congestion?

Consequently, when extending mobile cloud platforms using opportunistic networks, this requires a highly dynamic security and privacy solution that do not depend of a predefined communication path. To address such issues, a 'hop-based' security management mechanisms can be employed [Bogliolo et al., 2012]. This mechanism helps to establish a secure communication via data encryption between the nodes participating in a hop-to-hop message delivery.

5.4 Dynamic Resource Management

Resource management is vital as this helps users offloading data to infrastructure cloud. Data offloading can help to improve energy management of the mobile devices as well as reduce the unnecessary loss of network bandwidth utilisation [Kumar and Lu., 2010]. In a traditional on-premise application deployment model, user's private data is stored within a secure boundary based on an organisation's policy and fixed security infrastructure. But when extending mobile cloud platforms using opportunistic networks, it is impractical to enforce a flexed infrastructure for communication for resource management. Users must somewhat overcome the inherent uncertainty of an available contact opportunity, making them rely upon locally available infrastructures while hoping for the secure handling of their data [Li et al., 2015]. We indicate the open research questions for future research are as follows:

- How can we efficiently offload data at runtime that helps to improve the battery power and bandwidth utilisation within the network?
- How can we enhance dynamic resource management to effectively adjust congested conditions at runtime to reflect situational changes to the participants (nodes/users)?
- How to provide context-aware service discovery of nearby users (in proximity) that supports trustworthy service discovery based on social interactions?

To this end, security mechanisms based on privacy-preserving data mining technique can be employed [Mohammed et al., 2011]. This technique helps a better classification analysis of stored data based on a privacy-preserving manner by using a decision tree classifier. In this, the service provider keeps protect the user's sensitive data during the data mining process. Furthermore, for battery conservation the best approach would be to totally depend on the class of applications [Drolia et al., 2013].

5.5 Unpredictable User's Behaviour

In opportunistic networks, messages can be delivered from source to destinations through different users by storing, carrying and forwarding them when opportunity arises. Thus, unpredictable user's behaviour can lead to a higher delay or drop messages during the communication [Xu et al., 2009]. To this end, we indicate the open research questions for future research are as follows:

- Do proper incentive mechanisms help users to perform accordingly to transfer messages actively?

- How do the social reputations help others to encourage the transfer of messages accordingly?

Upon this, incentives for participating in message communication can be employed [Wang et al., 2012] [Scekic et al., 2013]. This may attract more users to participate actively in message forwarding. Incentives could be social reputations or in terms of money. Moreover, mechanisms for detecting user's selfish behaviour and encourage them to participate in message forwarding by providing attractive incentives are imperative [Ciobanu et al., 2014].

In table 4, we summarise the various open research questions and issues, their challenges and possible countermeasures (discussed in Section 5) when extending mobile cloud platforms using opportunistic networks. This includes user's privacy and security, heterogeneity of networks, node's mobility management, dynamic resource management and unpredictable user's behaviour.

Table 4: The table highlights the resulting challenges and their potential countermeasures/solutions that stem from the open research questions and issues when extending mobile cloud platforms using opportunistic networks.

Open Issues	***Challenges***	***Measures/Solutions***
User's privacy and security.	To preserve user's privacy and data confidentiality.	To employ dynamic privacy-aware framework [Wang., 2010].
Heterogeneity of networks.	Ensure secure communications for a node travelling via different network addresses.	To employ security mechanism that detect dynamic changes of networks accordingly and allow user's service preferences [Zhang et al., 2009].
Node's mobility management.	To keep the routing solutions highly dynamic and secure that does not dependent on a predefined path.	A hop-based security management mechanism can be employed [Bogliolo et al., 2012].
Dynamic resource management.	To improve the device's battery power and efficient network bandwidth utilisation.	Employ solutions dependent on the class of applications [Drolia et al., 2013].
Unpredictable user's behaviour.	To encourage people for participating in an active message forwarding.	Attractive incentive mechanisms can be employed [Scekic et al., 2013].

6 Conclusion

Rapid growth in cloud and mobile markets have led to huge demands to access cloud-based applications through mobile devices. But from the communication's point of view, the availability of Internet connections, network bandwidth and access costs are major barriers to overcome when using cloud-based applications seamlessly via mobile devices. On the other hand, from the device's point of view, major issues are limited battery power and memory size. In this paper, we survey the state of the art research advances and their limitations in mobile cloud technology. We then, explore the possibility of extending mobile cloud platforms using opportunistic networks in challenged environments. We devise a detailed classification of the difference mobile cloud architectures according to their mode of use. They are mobile cloud "Device to Cloud" (D2C) architecture, mobile cloud "Cloud to Device" (C2D) architecture and mobile cloud "Device to Device" (D2D) architecture. We have also explored the emergence of a new Mobile-Opportunistic Collaborative Cloud (MoCC) architecture that integrates the D2C, C2D and D2D class of mobile cloud architectures.

We discuss potential research issues related to the social and technological domains. In the social domain, user's mobility, social interactions, privacy and confidentiality of user's data are addressed. In the technological domain, the challenges of integrating mobile cloud technology and opportunistic networks for collaborative applications are discussed. We observe that it is feasible to use the MoCC architecture to avail a cloud-based application in rural/sparse areas that lacks an Internet connection for communication or in urban/dense areas with a high Internet roaming cost, instead of relying on a fixed infrastructure for communication.

We outline open issues and future research directions with their possible countermeasures on the state of the art research advancements in these areas. In future, we plan for more comprehensive experiments with real-life data sets to address the related open research questions and issues that are raised in this paper, which will in turn help to further our understanding towards making improvements in the performance of data-forwarding techniques in real-life scenarios.

Acknowledgement

The author would like to acknowledge the Scottish Informatics and Computer Science Alliance (SICSA) and the University of St Andrews, Scotland, United Kingdom. The author would like to thank the reviewers for their insightful comments on the paper. The author would also like to acknowledge to all the researchers for their ideas and works which have been presented in this paper.

References

[Abolfazli et al., 2014] S. Abolfazli, Z. Sanaei, E. Ahmed, A. Gani, and R. Buyya. Cloud-based augmentation for mobile devices: motivation, taxonomies, and open challenges. In: *IEEE Commun. Sur. & Tutorials*, vol. 16, no. 1, (2014), 337–368.

[Alam et al., 2015] M. M. Alam, D. B. Arbia, and E. B. Hamida. Research trends in multi-standard device-to-device communication in wearable wireless networks. In: *Cognitive Radio Oriented Wireless Networks.* Springer, (2015), 735–746.

[Ali et al., 2015] K. Ali, H. X. Nguyen, Q. T. Vien, and P. Shah. Disaster management communication networks: Challenges and architecture design. In: *International Conference on Pervasive Computing and Communication Workshops (PerCom Workshops).* IEEE, (2015), 537–542.

[Armbrust et al., 2010] M. Armbrust, A. Fox, R. Griffith, A. D. Joseph, R. Katz, A. Konwinski, G. Lee, D. Patterson, A. Rabkin, I. Stoica, and M. Zaharia. A View of Cloud Computing. In: *Commun. ACM*, vol. 53, no. 4, (2010), 50–58.

[Banerjee et al., 2013] Banerjee, A., Chen, X., Erman, J., Gopalakrishnan, V., Lee, S., Van Der Merwe, J. MOCA: A Lightweight Mobile Cloud Offloading Architecture. In: Proceedings of the Eighth ACM International Workshop on Mobility in the Evolving Internet Architecture, MobiArch, New York, USA, (2013), 11–16.

[Bhardwaj et al., 2014] K. Bhardwaj, S. Sreepathy, A. Gavrilovska, and K. Schwan. Ecc: Edge cloud composites. In: *The 2nd IEEE International Conference on Mobile Cloud Computing, Services, and Engineering (MobileCloud)*, (2014), 38–47.

[Bogliolo et al., 2012] A. Bogliolo, P. Polidori, A. Aldini, W. Moreira, P. Mendes, M. Yildiz, C. Ballester, and J. M. Seigneur. Virtual currency and reputation-based cooperation incentives in user-centric networks. In: *The 8th International Conference on Wireless Communications and Mobile Computing Conference (IWCMC).* IEEE, (2012), 895–900.

[Bulut and Szymanski., 2010] E. Bulut and B. K. Szymanski. Friendship based routing in delay tolerant mobile social networks. In: *IEEE Global Telecommunications Conference (GLOBECOM)*, IEEE, (2010), 1–5.

[Canepa et al., 2010] Huerta-Canepa, G., Lee, D. A virtual cloud computing provider for mobile devices. In: Proceedings of the 1st ACM Workshop on Mobile Cloud Computing; Services: Social Networks and Beyond, New York, USA, (2010), 61–65.

[Chandrasekhar et al., 2008] V. Chandrasekhar, J. G. Andrews, and A. Gatherer. Femtocell networks: a survey. In: *IEEE Communications Magazine*, vol. 46, no. 9, (2008), 59–67.

[Chang et al., 2012] Chang, C., Srirama, S., Ling, S. An adaptive mediation framework for mobile P2P social content sharing. In: C. Liu, H. Ludwig, F. Toumani, Q. Yu (eds.) Service-Oriented Computing, *Lecture Notes in Computer Science*, 7636, Springer Berlin Heidelberg, (2012), 374–388.

[Chang et al., 2013] Chang, R.S., Gao, J., Gruhn, V., He, J., Roussos, G., Tsai, W.T. Mobile Cloud Computing Research - Issues, Challenges and Needs. In: The 7th International Symposium on Service Oriented System Engineering (SOSE), IEEE, (2013), 442–453.

[Chen et al., 2004] Chen, G., Kang, B., Kandemir, M., Vijaykrishnan, N., Irwin, M., Chandramouli, R. Studying energy trade offs in offloading computation/compilation in java-enabled mobile devices. In: IEEE Transactions on Parallel and Distributed Systems, vol. 15, no. 9, (2004), 795–809.

[Cheng et al., 2015] R. G. Cheng, N. S. Chen, Y. F. Chou, and Z. Becvar. Offloading multiple mobile data contents through opportunistic device-to-device communications. In: *Wireless Personal Communications*, Springer, (2015), 1–17.

[Chun and Maniatis., 2010] Chun, B. G., Maniatis, P. Dynamically partitioning applications between weak devices and clouds. In: Proceedings of the 1st ACM Workshop on Mobile Cloud Computing; Services: Social Networks and Beyond, New York, USA, (2010), 71–75.

[Ciobanu et al., 2014] R. I. Ciobanu, C. Dobre, M. Dascălu, Ş. Trăuşan-Matu, and V. Cristea. Sense: A collaborative selfish node detection and incentive mechanism for opportunistic networks. In: *Journal of Network and Computer Applications*, vol. 41, (2014), 240–249.

[Conti et al., 2011] Conti, M., Chong, S., Fdida, S., Jia, W., Karl, H., Lin, Y. D., Mähönen, P., Maier, M., Molva, R., Uhlig, S., Zukerman, M. Research challenges towards the future Internet. Computer Communications, vol. 34, no. 18, (2011), 2115–2134.

[Conti and Giordano., 2014] M. Conti and S. Giordano. Mobile ad hoc networking: milestones, challenges, and new research directions. In: *IEEE Communications Magazine*, vol. 52, no. 1, (2014), 85–96.

[Conti and Kumar., 2010] M. Conti and M. Kumar. Opportunities in Opportunistic Computing. In: *Computer*, vol. 43, no. (1), (2010), 42–50.

[Dinh et al., 2013] H. T. Dinh, C. Lee, D. Niyato, and P. Wang. A survey of mobile cloud computing: architecture, applications, and approaches. In: *Wireless communications and mobile computing*, vol. 13, no. 18, (2013), 1587–1611.

[Drolia et al., 2013] U. Drolia, R. P. Martins, J. Tan, A. Chheda, M. Sanghavi, R. Gandhi, and P. Narasimhan. The case for mobile edge-clouds. In: *The 10th International Conference on Ubiquitous Intelligence and Computing (UIC).* IEEE, (2013), 209–215.

[Fernando et al., 2012] Fernando, N., Loke, S. W., Rahayu, W. Mobile Crowd Computing with Work Stealing. In: The 15th International Conference on Network-Based Information Systems (NBiS), IEEE, (2012), 660–665.

[Fernando et al., 2013] Fernando, N., Loke, S. W., Rahayu, W. Mobile cloud computing: A survey. In: Future Generation Computer Systems, vol. 29, no. (1), (2013), 84–106.

[Garcia et al., 2009] Garcia-Bauelos, L., Portilla, A., Chavez-Aragon, A., Reyes-Galaviz, O.F., Ayanegui-Santiago, H. Finding and Analyzing Social Collaboration Networks in the Mexican Computer Science Community. In: IEEE Mexican International Conference on Computer Science (ENC), (2009), 167–175.

[Girolami et al., 2015] M. Girolami, S. Chessa, and A. Caruso. On service discovery in mobile social networks: Survey and perspectives. In: *Computer Networks*, vol. 88, (2015), 51–71.

[Giurgiu et al., 2009] Giurgiu, I., Riva, O., Juric, D., Krivulev, I., Alonso, G. Calling the cloud: Enabling mobile phones as interfaces to cloud applications. In: J. Bacon, B. Cooper (eds.) Middleware 2009, *Lecture Notes in Computer Science*, vol. 5896, Springer Berlin Heidelberg, (2009), 83–102.

[Gretzel et al., 2015] U. Gretzel, H. Werthner, C. Koo, and C. Lamsfus. Conceptual foundations for understanding smart tourism ecosystems In: *Computers in Human Behavior*, vol. 50, (2015), 558-563.

[Han et al., 2015] Q. Han, S. Liang, and H. Zhang. Mobile cloud sensing, big data, and 5g networks make an intelligent and smart world. In: IEEE Netwroks, vol. 29, no. 2, (2015), 40–45.

[Huang et al., 2008] C. M. Huang, K. chan Lan, and C. Z. Tsai. A survey of opportunistic networks. In: *The 22nd International Conference on Advanced Information Networking and Applications - Workshops (AINAW)*, (2008), 1672–1677.

[Huang et al., 2010] Huang, D., Zhang, X., Kang, M., Luo, J. MobiCloud: Building Secure Cloud Framework for Mobile Computing and Communication. In: *The Fifth IEEE International Symposium on Service Oriented System Engineering (SOSE)*, (2010), 27–34.

[Hui et al., 2009] P. Hui, K. Xu, V. O. Li, J. Crowcroft, V. Latora, and P. Lio. Selfishness, altruism and message spreading in mobile social networks. In: *INFOCOM Workshops.* IEEE, (2009), 1–6.

[Hui and Crowcroft., 2007] P. Hui and J. Crowcroft. How small labels create big improvements. In: *Proceedings of the Fifth International Conference on Pervasive Computing and Communications Workshops*, IEEE Computer Society, Washington DC, USA, (2007), 65–70.

[Hung et al., 2011] Hung, J. C., Hsu, V., Wang, Y. B. A Smart-Travel System Based on Social Network Service for Cloud Environment. In: The Third International Conference on Intelligent Networking and Collaborative Systems (INCoS), IEEE, (2011), 514–519.

[Jin et al., 2013] L. Jin, Y. Chen, T. Wang, P. Hui, and A. V. Vasilakos. Understanding user behavior in online social networks: A survey. In: *IEEE Communications Magazine*, vol. 51, no. 9, (2013), 144–150.

[Jin and Kwok., 2010] Jin, X., Kwok, Y. K. Cloud Assisted P2P Media Streaming for Bandwidth Constrained Mobile Subscribers. In: The 16th International Conference on Parallel and Distributed Systems (ICPADS), IEEE, (2010), 800–805.

[Karamshuk et al., 2011] D. Karamshuk, C. Boldrini, M. Conti, and A. Passarella. Human mobility models for opportunistic networks. In: *IEEE Communications Magazine*, vol. 49, no. 12, (2011), 157–165.

[Karim and Mahmoud., 2013] L. Karim and Q. H. Mahmoud. A hybrid mobility model based on social, cultural and language diversity. In: *The 9th International Conference Conference on Collaborative Computing: Networking, Applications and Worksharing (Collaboratecom).* IEEE, (2013), 197–204.

[Karvounas et al., 2014] D. Karvounas, A. Georgakopoulos, K. Tsagkaris, V. Stavroulaki, and P. Demestichas. Smart management of D2D constructs: an experiment-based approach. In: *IEEE Communications Magazine*, vol. 52, no. 4, (2014), 82–89.

[Kemp et al., 2012] R. Kemp, N. Palmer, T. Kielmann, and H. Bal. Cuckoo: a computation offloading framework for smartphones. In: *Mobile Computing, Applications, and Services.* Springer, (2012), 59–79.

[Kevin., 2003] Fall, K. A delay-tolerant network architecture for challenged internets. In: Proceedings of the 2003 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications, SIGCOMM, USA (2003), 27–43.

[Khan et al., 2013] Khan, A., Othman, M., Madani, S., Khan, S. A Survey of Mobile Cloud Computing Application Models. In: IEEE Communications Surveys & Tutorials, vol. 16, no. 1, (2013), 1–21.

[Keshav., 2010] Keshav, S. Design principles for robust opportunistic communication. In: Proceedings of the 4th ACM Workshop on Networked Systems for Developing Regions, New York, USA, (2010), 61–66.

[Klein et al., 2010] Klein, A., Mannweiler, C., Schneider, J., Schotten, H.D. Access Schemes for Mobile Cloud Computing. In: The Eleventh International Conference on Mobile Data Management (MDM), IEEE, Washington DC, USA, (2010), 387–392.

[Koukoumidis et al., 2011] Koukoumidis, E., Lymberopoulos, D., Strauss, K., Liu, J., Burger, D. Pocket Cloudlets. In: SIGARCH Comput. Archit. News, vol. 39, no. 1, (2011), 171–184.

[Kumar et al., 2010] R. Kumar, J. Novak, and A. Tomkins. Structure and evolution of online social networks. In: *Link mining: models, algorithms, and applications*. Springer, (2010), 337–357.

[Kumar and Lu., 2010] Kumar, K., Lu, Y. H. Cloud computing for mobile users: Can offloading computation save energy?. In: IEEE Computer, vol. 43, no. 4, (2010), 51–56.

[Lei et al., 2013] Lei, L., Zhong, Z., Zheng, K., Chen, J., Meng, H. Challenges on wireless heterogeneous networks for mobile cloud computing. In: Wireless Communications, IEEE, vol. 20, no. (3), (2013). 34–44.

[Li et al., 2009] Li, X., Zhang, H., Zhang, Y. Deploying Mobile Computation in Cloud Service. In: M.G. Jaatun, G. Zhao, C. Rong (eds.) Cloud Computing, *Lecture Notes in Computer Science*, 5931, 27, Springer Berlin Heidelberg, Berlin, Heidelberg (2009), 301–311.

[Li et al., 2014] B. Li, Z. Liu, Y. Pei, and H. Wu. Mobility prediction based opportunistic computational offloading for mobile device cloud. In: *The 17th International Conference on Computational Science and Engineering (CSE)*. IEEE, (2014), 786–792.

[Li et al., 2014] Y. Li, T. Wu, P. Hui, D. Jin, and S. Chen. Social-aware d2d communications: qualitative insights and quantitative analysis. In: *IEEE Communications Magazine*, vol. 52, no. 6, (2014), 150–158.

[Li et al., 2015] J. Li, X. Tan, X. Chen, D. Wong, and F. Xhafa. Opor: Enabling proof of retrievability in cloud computing with resource-constrained devices. In: *IEEE Transactions on Cloud Computing*, vol. 3, no. 2, (2015), 195–205.

[Li and Guo., 2015] P. Li and S. Guo. Incentive mechanisms for device-to-device communications. In: *IEEE Network*, vol. 29, no. 4, (2015), 75–79.

[Lilien et al., 2007] L. Lilien, Z. H. Kamal, V. Bhuse, and A. Gupta. The concept of opportunistic networks and their research challenges in privacy and security. In: *Mobile and wireless network security and privacy*. Springer, (2007), 85–117.

[Lindgren et al., 2004] A. Lindgren, A. Doria, and O. Schelén. Probabilistic Routing in Intermittently Connected Networks. In: *Service Assurance with Partial and Intermittent Resources (SAPIR)*, Fortaleza, Brazil, (2004), 239–254.

[Marin et al., 2015] R. C. Marin, R. I. Ciobanu, R. Pasea, V. Barosan, M. Costea, and C. Dobre. Context-awareness in opportunistic mobile cloud computing. In: *Resource Management of Mobile Cloud Computing Networks and Environments*, (2015), 203.

[Marinelli., 2009] E. E. Marinelli. Hyrax: cloud computing on mobile devices using mapreduce. In: Carnegie-mellon univ, Pittsburgh PA, school of computer science, Tech. Rep., (2009).

[Mascitti et al., 2014] D. Mascitti, M. Conti, A. Passarella, and L. Ricci. Service provisioning through opportunistic computing in mobile clouds. In: *Proceedings of the Fourth International Conference on Selected Topics in Mobile & Wireless Networking (MoWNet2014)*, vol. 40, (2014), 143–150.

[Mell and Grance., 2009] P. Mell and T. Grance. The NIST definition of cloud computing. vol. 53, no. 6. McKinsey Global Institute, (2009), 50.

[Meng et al., 2015] T. Meng, Q. Wang, and K. Wolter. Model-based quantitative security analysis of mobile offloading systems under timing attacks. In: *Analytical and Stochastic Modelling Techniques and Applications*. Springer, (2015), 143–157.

[Miluzzo et al., 2012] Miluzzo, E., Cáceres, R., Chen, Y.F. Vision: mClouds - computing on clouds of mobile devices. In: Proceedings of the third ACM workshop on Mobile cloud computing and services, New York, USA, (2012), 9–14.

[Mohammed et al., 2011] N. Mohammed, R. Chen, B. Fung, and P. S. Yu. Differentially private data release for data mining. In: *Proceedings of the 17th ACM SIGKDD international conference on Knowledge discovery and data mining*. ACM, (2011), 493–501.

[Moreira and Mendes., 2013] W. Moreira and P. Mendes, Social-Aware Opportunistic Routing: The New Trend. In: *Routing in Opportunistic Networks*, I. Woungang, et al., (eds.) Springer, New York, (2013), 27–68.

[Moreira and Mendes., 2015] W. Moreira and P. Mendes. Impact of human behavior on social opportunistic forwarding. In: *Ad Hoc Networks*, vol. 25, (2015), 293–302.

[Mtibaa et al., 2013] Mtibaa, A., Harras, K.A., Fahim, A. Towards Computational Offloading in Mobile Device Clouds. In: The IEEE 5th International Conference on Cloud Computing Technology and Science (CloudCom), vol. 1, (2013), 331–338.

[Nguyen et al., 2014] A. D. Nguyen, P. Senac, and M. Diaz. Behavioral and structural analysis of mobile cloud opportunistic networks. In: *Opportunistic Mobile Social Networks*, (2014), 123.

[Orlinski and Filer., 2015] M. Orlinski and N. Filer. Neighbour discovery in opportunistic networks. In: *Ad Hoc Networks*, vol. 25, (2015), 383–392.

[Ou et al., 2007] Ou, S., Yang, K., Liotta, A., Hu, L. Performance analysis of offloading systems in mobile wireless environments. In: *IEEE International Conference on Communications (ICC)*, (2007), 1821–1826.

[Pal and Henderson., 2013] Pal, S., Henderson, T. MobOCloud: Extending Cloud Computing with Mobile Opportunistic Networks. In: Proceedings of the 8th MobiCom Workshop on Challenged Networks (CHANTS'13), ACM, Florida, USA, (2013), 57–62.

[Papakos et al., 2010] Papakos, P., Capra, L., Rosenblum, D.S. VOLARE: Context-aware Adaptive Cloud Service Discovery for Mobile Systems. In: Proceedings of the 9th International Workshop on Adaptive and Reflective Middleware, New York, USA, (2010), 32–38.

[Pedersen and Fitzek., 2012] Pedersen, M.V., Fitzek, F.H.P. Mobile Clouds: The New Content Distribution Platform. In: Proceedings of the IEEE 100(Special Centennial Issue), (2012), 1400–1403.

[Pejovic and Musolesi., 2015] V. Pejovic and M. Musolesi. Anticipatory mobile computing: A survey of the state of the art and research challenges. In: *ACM Computing Surveys (CSUR)*, vol. 47, no. 3, (2015), 1–29.

[Qi and Gain., 2012] Qi, H., Gani, A. Research on mobile cloud computing: Review, trend and perspectives. In: *The Second International Conference on Digital Information and Communication Technology and it's Applications (DICTAP)*, IEEE, (2012), 195–202.

[Qiu et al., 2015] L. Qiu, H. Rui, and A. Whinston. When cellular capacity meets wifi hotspots: A smart auction system for mobile data offloading. In: *The 48th Hawaii International Conference on System Sciences (HICSS)*. IEEE, (2015), 4898–4907.

[Rahimi et al., 2014] M. R. Rahimi, J. Ren, C. H. Liu, A. V. Vasilakos, and N. Venkatasubramanian. Mobile cloud computing: A survey, state of art and future directions. In: *Mobile Networks and Applications*, vol. 19, no. 2, (2014), 133–143.

[Ravi et al., 2008] Ravi, N., Scott, J., Han, L., Iftode, L. Context-aware battery management for mobile phones. In: The Sixth Annual IEEE International Conference on Pervasive Computing and Communications, (2008), 224–233.

[Ren et al., 2015] J. Ren, Y. Zhang, K. Zhang, and X. Shen. Exploiting mobile crowdsourcing for pervasive cloud services: challenges and solutions. In: *IEEE Communications Magazine*, vol. 53, no. 3, (2015), 98–105.

[Samimi et al., 2006] Samimi, F., McKinley, P., Sadjadi. Mobile Service Clouds: A Self-Managing Infrastructure for Autonomic Mobile Computing Services. In: A. Keller, J.P. Martin-Flatin (eds.) Self-Managed Networks, Systems, and Services, *Lecture Notes in Computer Science*, 3996, Springer, Berlin Heidelberg, (2006), 130–141.

[Sanaei et al., 2014] Z. Sanaei, S. Abolfazli, A. Gani, and R. Buyya. Heterogeneity in mobile cloud computing: taxonomy and open challenges. In: *IEEE Communications Surveys & Tutorials*, vol. 16, no. 1, (2014), 369–392.

[Sapuppo., 2010] Sapuppo, A. Spiderweb: A social mobile network. In: Wireless Conference (EW), European, (2010), 475-481.

[Satyanarayanan et al., 2009] M. Satyanarayanan, P. Bahl, R. Caceres, and N. Davies. The case for vm-based cloudlets in mobile computing. In: *Pervasive Computing, IEEE*, vol. 8, no. 4, (2009), 14–23.

[Scekic et al., 2013] O. Scekic, H. L. Truong, and S. Dustdar. Incentives and rewarding in social computing. In: *Commun. ACM*, vol. 56, no. 6, (2013), 72–82.

[Shen et al., 2010] Shen, J., Yan, S., Hua, X.S. The e-Recall Environment for Cloud Based Mobile Rich Media Data Management. In: Proceedings of the ACM Multimedia Workshop on Mobile Cloud Media Computing, New York, USA, (2010), 31–34.

[Shi et al., 2014] C. Shi, K. Habak, P. Pandurangan, M. Ammar, M. Naik, and E. Zegura. Cosmos: computation offloading as a service for mobile devices. In: *Proceedings of the 15th ACM international symposium on Mobile ad hoc networking and computing*. ACM, (2014), 287–296.

[Shi et al., 2014] T. Shi, M. Yang, Y. Jiang, X. Li, and Q. Lei. An adaptive probabilistic scheduler for offloading time-constrained tasks in local mobile clouds. In: *The Sixth International Conference on Ubiquitous and Future Networks (ICUFN)*, IEEE, (2014), 243–248.

[Shikfa., 2010] Shikfa, A. Security issues in opportunistic networks. In: Proceedings of the Second International Workshop on Mobile Opportunistic Networking (MobiOpp), Pisa, Italy, (2010), 215–216.

[Slabeva and Wozniak., 2010] Stanoevska-Slabeva, K., Wozniak, T. Cloud Basics An Introduction to Cloud Computing. In: K. Stanoevska-Slabeva, T. Wozniak, S. Ristol (eds.) Grid and Cloud Computing, chap. 4, Springer, Berlin Heidelberg, (2010), 47–61.

[Spyropoulos et al., 2005] T. Spyropoulos, K. Psounis, and C. S. Raghavendra. Spray and wait: An efficient routing scheme for intermittently connected mobile networks. In: *SIGCOMM Workshop on Delay-tolerant Networking*, PA, USA, (2005), 252–259.

[Swierk and Baker., 1999] M. R. P. M. E. Swierk and K. L. G. A. M. Baker. Person-level routing in the mobile people architecture. In: *Proceedings of the USENIX Symposium on Internet Technologies and Systems*, vol. 2. Usenix Assoc, (1999), 165.

[Toninelli et al., 2011] Toninelli, A., Pathak, A., and Issarny, V. Yarta: A middleware for managing mobile social ecosystems. In: J. Riekki, M. Ylianttila, M. Guo (eds.) Advances in Grid and Pervasive Computing, *Lecture Notes in Computer Science*, 6646, (2011), 209–220.

[Vahdat and Becker., 2000] A. Vahdat and D. Becker. Epidemic Routing for Partially-Connected Ad Hoc Networks. In: Technical Report CS-200006, Duke University, (2000).

[Verbelen et al., 2012] Verbelen, T., Simoens, P., De Turck, F., Dhoedt, B. Cloudlets: bringing the cloud to the mobile user. In: Proceedings of the third ACM workshop on Mobile cloud computing and services, New York, USA (2012), 29–36.

[Wang., 2010] H. Wang. Privacy-preserving data sharing in cloud computing. In: *Journal of Computer Science and Technology*, vol. 25, no. 3, (2010), 401–414.

[Wang et al., 2012] Wang, Y., Chuah, M. C., Chen, Y. Incentive driven information sharing in delay tolerant mobile networks. In: IEEE Global Communications Conference (GLOBECOM), (2012), 5279-5284.

[Wang et al., 2015] X. Wang, G. Han, X. Du, and J. Rodrigues. Mobile cloud computing in 5g: Emerging trends, issues, and challenges [guest editorial]. In: *IEEE Network*, vol. 29, no. 2, (2015), 4–5.

[Whipple et al., 2009] J. Whipple, W. Arensman, and M. S. Boler. A public safety application of gps-enabled smartphones and the android operating system. In: *International Conference on Systems, Man and Cybernetics (SMC).* IEEE, (2009), 2059–2061.

[Xin., 2009] Xin, C. Mobile Phone Operating System Choice in Mobile Phone Game from Market Prospect. In: The International Conference on Industrial and Information Systems (IIS), IEEE, (2009), 188–190.

[Xu et al., 2009] K. Xu, P. Hui, V. O. Li, J. Crowcroft, V. Latora, and P. Lio. Impact of altruism on opportunistic communications. In: *The First International Conference on Ubiquitous and Future Networks (ICUFN).* IEEE, (2009), 153–158.

[Zhang et al., 2009] X. Zhang, J. Schiffman, S. Gibbs, A. Kunjithapatham, and S. Jeong. Securing elastic applications on mobile devices for cloud computing. In: *Proceedings of the ACM workshop on Cloud computing security.* ACM, (2009), 127–134.

[Zhang et al., 2015] H. Zhang, Y. Li, D. Jin, and S. Chen. Selfishness in device-to-device communication underlaying cellular networks. In: ICC, Workshop on Device-to-Device Communication for Cellular and Wireless Networks, London, United Kingdom, (2015), 1–5.

[Zhiwen et al., 2011] Yu, Z., Liang, Y., Xu, B., Yang, Y., Guo, B. Towards a smart campus with mobile social networking. In: Internet of Things (iThings/CPSCom), International Conference on and 4th International Conference on Cyber, Physical and Social Computing, (2011), 162–169.

[Zhou et al., 2015] B. Zhou, A. V. Dastjerdi, R. N. Calheiros, S. N. Srirama, and R. Buyya. A context sensitive offloading scheme for mobile cloud computing service. In: *The 8th International Conference on Cloud Computing (CLOUD).* IEEE, (2015), 869–876.